PRESSURE - ENTHALPY CHARTS

FOR

WATER AND STEAM

Calculated and Delineated
With Special Reference to the Solution
of Problems in the Field of
Advanced Thermodynamics.

A Thesis

Submitted for the Degree of

MASTER OF SCIENCE

in

MECHANICAL ENGINEERING

by

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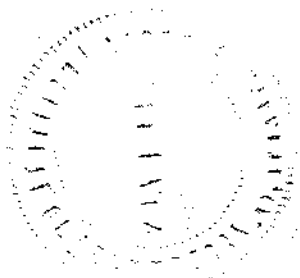

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FOREWORD

The Charts presented in this work have been constructed with the hope that they may in some manner fill a place in engineering. It is the author's belief that they may make certain computations much easier and lighten the drudgery that oftimes accompanies the long and tedious computations encountered in any field involving water, steam, and their mixtures.

The Charts are accompanied by a few pages of definition of terms and properties; a slight historical discussion; a portion of theoretical and mathematical material. These may throw light upon processes which were used by the author or by those whose material has been used as source matter in the development of the Charts. A few examples of how the Charts may be used in practical work have been placed adjacent to the Charts with a Skeleton Chart prepared as a guide for the beginner.

The author wishes to thank the members of the faculty of the Mechanical Engineering Department of the Georgia School of Technology for their kind assistance during the preparation of this Thesis, particularly Dr. R. S. King, for constructive criticisms and encouragement, and Prof. Newton C. Ebaugh for valuable suggestions in preparation of the Charts.

DEFINITIONS

In order that the student or engineer using these Charts may proceed without uncertainty, the author has prepared a few definitions and descriptive notes in regard to terms used in the Thesis and to the properties shown on the Charts. Further definitions or explanations may be found in any standard text on Thermodynamics.

ENERGY is defined as the ability to produce an effect.

HEAT is defined as thermal energy which passes into or passes from a thermodynamic system by reason of a difference of temperature. Heat is one of the two forms of transient energy, the other form having the name, Work. Heat may pass into or out of a system by one of two processes, conduction or radiation. The process, convection, which has been assigned in the past as a third form of heat transfer, is really the transfer of the system itself from one location to another, carrying its various forms of stored energy along with it.

SPECIFIC HEAT is defined as the rate of adding heat in respect to the temperature rise of the system.

The Specific Heat of water is variable. With the Charts presented herewith, there is little need of using specific heat. The enthalpy values on the Charts may be used.

SPECIFIC HEAT of superheated steam takes up no little space in the pages of many commentaries. However, with a good set of steam charts, any addition of heat may be determined directly without reference to the rate of adding same. It is unnecessary when adequate charts are available to be concerned over the questions of mean specific heats or instantaneous specific heats. Accurate investigations have been made which have determined the heat rates and these Charts are prepared after adequate consultation with the results of these experiments.

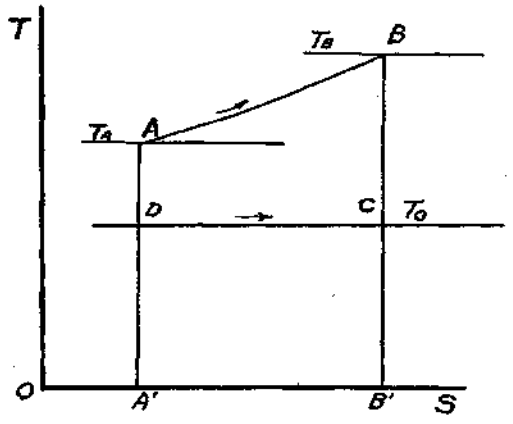
ENERGY OF THE LIQUID is synonymous with the enthalpy of the liquid and has recently been adopted by many prominent writers on Thermodynamics in place of the confusing term, heat of the liquid. (See Enthalpy.)

ENERGY OF EVAPORATION is the increase of enthalpy during the process of ebulition of water into steam. This term is used in place of the former confusing term, heat of evaporation.

ENTROPY is a property of a Thermodynamic system which has been devised in order to facilitate calculations of the changes of other properties. It has been defined as that property of a system, the increase (decrease) of which is the quotient of the increase (decrease) of unavailable energy and the absolute receiver temperature. Its significance then is that of

an index of the unavailability of the heat added to a system, since the heat added to the system is composed of both available and unavailable energy.

The accompanying figure shows that as heat is added from A at temperature TA to B at temperature T_B, the area ABB'A', representing the heat added, is composed of two parts, ABCD above the lowest naturally achieved temperature, T_o, and DCB'A' below T_o. ABCD is the maximum available energy and DCB'A' is the minimum unavailable energy. The increase of entropy DC during the process of adding ABB'A' is therefore equal to the unavailable part added, DCB'A', divided by the absolute receiver temperature, T_o.



The Entropy of a system may be further defined by the following list of characteristics:

1. Depends upon the weight
2. Is the sum of the increase of entropies during any states passed through in reaching the condition

3. Is relative to an arbitrarily determined zero
4. Has the unit, B.T.U. per degree Fahrenheit
5. Is a function of the state of the system
6. Can therefore be used as a co-ordinate, and
7. Can be determined for a reversible process by the solution of $\int \frac{dq}{T}$ or for a non-reversible process by the sum of the integrals for several equivalent reversible processes.

ENERGY OF SUPERHEAT is the amount of heat added at the existing pressures from the condition of dry and saturated steam to a desired temperature above the saturation temperature for the existing pressure.

DEGREE OF SUPERHEAT is the temperature difference between the existing temperature and the saturation temperature corresponding to the existing pressure.

QUALITY is the percent dryness of a mixture of water and its vapor.

MOISTURE is the percent wetness of a mixture of water and its vapor. The sum of the quality and the moisture of a mixture is equal to unity.

SPECIFIC VOLUME is cubic feet per unit weight. It is the reciprocal of density which is weight per cubic foot.

ENTHALPY may be defined as the sum of the internal energy and the flow work of a fluid. Though both of these energy quantities are actually above zero energy, the usual and most convenient practice is to quote internal energy, flow work (sometimes called external work) and consequently their sum, enthalpy, above some arbitrarily assigned datum point, at which all three are assumed to be zero. In present day practice, this datum point is for water and steam, 32° F. and its corresponding saturation pressure, 0.0887 pounds per square inch. Another conception of Enthalpy is that its increase (or decrease) is the heat added (rejected) to a vapor at the pressure under discussion. That is, Enthalpy is the heat added at constant pressure which would be utilized by the medium in an increase of internal energy and in furnishing the work energy to force back any exterior systems and provide the space necessary for the increase of volume of the vapor.

The name "Enthalpy", which has been called the chi function by many writers, notable among whom was Willard Gibbs, has replaced a large number of names most of which have been confusing either due to the inaccurate or ambiguous implications. Some of these are total heat, heat content, thermal potential, thermal head. Those terms which contained

the word HEAT(heat content or total heat), intimated that all of the energy transferred to a system would be present in the system. This is not true since the PV portion is not stored energy in any sense. There are several other "potentials" so that the name, "thermal potential", is quite confusing. Thermal head has hydraulic implications that have a tendency to be misleading.

FRICTIONLESS ADIABATIC PROCESSES are those which are accompanied by constant entropy processes. Any other processes will be accompanied by a variation of entropy dependant upon whether the unavailable portion of the energy is increased or decreased.

WORK is a form of energy caused by a force acting through a distance. It may also be caused by a pressure being exerted upon a system such that a change of volume may result.

POWER is the rate of doing work. Power is a function of the time. The work of a cycle is the equivalent of the algebraic sum of the heats added and rejected during the cycle.

MECHANICAL EQUIVALENT OF HEAT is the factor used to transform energy in heat units into energy in work units. This factor has its being as a corollary of the law of conservation of energy.

A FLUID may be thought of as any medium which has the properties of flowing. The usual classification of

of fluids is LIQUIDS, VAPORS, and GASES. It is true with few exceptions that a compound or element may at different values of its fundamental properties, temperature, pressure and specific volume (or its reciprocal, density), be found in each of these classes. Many fluids may go entirely below this fluid classification and become solids.

HISTORICAL DISCUSSION

Since Fluids as defined above may pass from one of these afore mentioned classes (liquid, vapor, gas) into another with varying values of the properties, it is a convenience and usually a necessity that tables and charts be prepared that will make it easy to determine which form the medium may possess at certain values of the properties, and how certain of the principal and derived properties vary as one or more is independently changed.

Among the charts which have been most useful in the analysis of vapor cycles are those known as "Mollier Diagrams" and the Pressure-Volume diagram. Though a number of diagrams have been designated by the name "Mollier", the man who constructed early charts for steam, the one usually designated is the Enthalpy-Entropy (Heat-Entropy) Chart. For the sake of analysis and for the purpose of instruction, another chart, the Temperature-Entropy, has been found very useful.

The Ellenwood Charts were published first in 1914, the principal one being the Enthalpy-Constant Volume (Total Heat-Volume) Chart with other properties drawn in. Supplementary to this was the chart with A PV and V as coordinates. All of these charts have their specific uses. The one developed in this thesis has a number of very particular uses which are mentioned and explained in detail later.

For many years the Marks and Davis steam tables and accompanying charts have been used and have served a very fine purpose in engineering work.

The results of the Davis-Kleinschmidt Joule-Thomson tests were presented to the annual meeting of the American Society of Mechanical Engineers in December 1923. The General Electric Company developed charts with permission of Dr. Harvey N. Davis. Mr. George A. Orrok, Chairman of the A.S.M.E. Committee on Properties of Steam, was cordially interested and kindly gave access to all data of that Committee. The General Electric Company chart was constructed for Enthalpy-Entropy (Total heat-Entropy) between the pressures of 0.2 pounds per square inch and 750 pounds per square inch and up to 800° F. Volume Tables were later developed in the range of 1 pound per square inch and 1200 pounds per square inch and 400° F. Superheat. These were calculated from tests and from the evaluation of

$$\left(\frac{d\phi}{dp}\right)_T$$

Keenan Tables have been produced in America developed from data resulting from tests by L. B. Smith and F. G. Keyes of Massachusetts Institute of Technology; E. S. Mueller, N. S. Osborne, H. F. Stimson, E. P. Fioch, and associates of U. S. Bureau of Standards; R. C. H. Herk of Rutgers College; A. D. Risteen; H. N. Davis, President of Stevens Institute; Lionel S. Marks of Harvard University; F. O. Ellenwood of Cornell University; M. C. Steart; C. H. Berry; and George A. Orrok, consulting Engineer

E. L. Robinson of the Turbine Engineering Department of General Electric Company and Joseph H. Keenan formerly of General Electric Company and at present of Stevens Institute, and others.

According to the opinion of Dr. Jakob in four lectures delivered before the University of London in the spring and summer of 1931, as quoted in Mechanical Engineering, Volume 54, April and May 1932, steam engineering until recently had made greater advance than steam physics with pressures exceeding that of the critical point, 3226 pounds per square inch and progressing to temperatures of 1000° F. Physical science has followed slowly, partly because the investigation of high pressure and superheated steam was possible only with proper apparatus, the construction and use of which was not familiar to physicists. He refered to work previously done, such as that of Professor Callendar, which he considers of high order, and of other investigations, including his own, under Professor Knoblauch, and that of Osborne in America. He also cited the more recent investigations carried out in Czechoslovakia, England, Germany and the United States.

All these investigations, he said, were undertaken for the purpose of determining for water and steam,

at all possible pressures and temperatures: (1) The specific volume, for calculation of the dimensions of steam engines; and (2) the enthalpy, for evaluating the heat balance of the same engines. These were effected by direct measurements, or by indirect methods, namely, by using molecular or thermodynamic relations, leading from the volume to the enthalpy, and vice versa. Nearly all possible paths to this end have been traversed.

In considering the fundamental thermodynamic properties of water and steam, Dr. Jakob began with the direct measurement of the characteristic values p,v, and T, and gave a table summarizing the different measurements of these values with the names of investigators. The saturation line of steam was measured in Germany by Holborn and Henning, and at higher pressures up to the critical point by Holborn and Baumann. The new American measurements of Keys and Smith gave nearly the same values, namely, 225.8 atm. and 374.1° C. Above 100 kg. per sq. cm., however, Keyes found higher saturation pressures than Holborn, the difference reaching nearly 0.5 kg. per sq. cm. at 220 kg. per sq. cm. In England, Egerton and Callendar, Jr., quite recently checked these results against their own measurements and obtained close agreement with the German observations. According to the measurements

and theoretical considerations of the late Professor Callendar, there should exist, above 225 kg. per sq.cm. and 374° C., an unstable region, in which water and steam form mixtures, and only above 257 kg. per sq.cm. and 380.5° C. is a uniform state to be found.

The thermometers and gages which were used in these measurements were described in the original text, which also describes the instruments used in other measurements. None of these descriptions were reported in Mechanical Engineering because of lack of space.

A particular lack of knowledge has existed until recently regarding the specific volume of water, but this deficiency has been made good by recent experiments in America, England, and Germany. The values obtained by several experimenters were given in a table in the original text. The values up to 300° C. and 250 kg. per sq.cm. agreed with one another within 0 to 0.9 per cent; those up to 320° C. and 300 kg. per sq. cm. within 1.3 per cent; near saturation above 320° C. the values of Trautz and Steyer were too high by a maximum of 3.7 per cent.

The specific volume of steam up to 10 atm. was determined more than twenty-five years ago by Knoblauch, Linde, and Klebe, of Munich. Today the results of the

measurements of Keyes and Smith have also been made available. These experiments cover specific volumes from 5 to 150 cu. cm. per gram, a pressure range from 1 to 183 (partially even to 246) kg. per sq.cm. and temperatures from 200 to 460 C. Professor Callendar, however, has proceeded the farthest, namely, even beyond the critical point. More than thirty years ago Callendar established, by measurements in a steam engine and otherwise the following equations referring to the adiabatic change of state of superheated steam:

$$pv^{1.3} = \text{constant}$$

$$vr^{10/3} = \text{constant}$$

in which v is the specific volume, if the correction for covolume, as the specific volume of the molecules themselves has been named by van der Waals, is neglected.

Callendar carried out measurements of the specific volume near the critical point which led to such curious results that he did not try to publish them until about twenty years later. In these experiments, Callendar found that at 374° C. the densities of the liquid and the vapor were not equal as demanded by the theory of van der Waals and as observed by earlier investigators.

Contrary to this, as can be seen from Figure 1, the density of water was found to be about 0.435, while that of steam was about 0.26 gram per cu.cm. Only at 380.5° C (corresponding to 257 instead of 225 technical atmospheres) do the values coincide at the density of 0.375. The upper curve (for water) is observed, and the lower curve is interpolated.

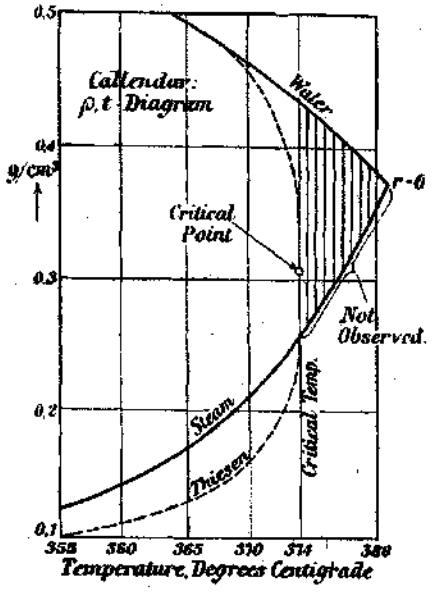


FIG. 1 TEMPERATURE-DENSITY CURVES FOR STEAM AND WATER

According to this, Professor Callendar supposed that, above 374° C., there existed an unstable region in which water and steam were mixed intimately. In this region, instead of a meniscus, there was to be seen a demarcation line, as was the case in layers of two liquids having nearly the same density. To maintain this appearance, absolutely pure steam was essential; Professor Callendar stated that the air contained in his steam was only one 10^9th part of the total weight. With the least impurity of the steam, mist was formed, and the line separating the two substances vanished.

Since excellent new observations of the specific volume had been made in the region of liquid water, as well as in that of superheated steam, these observations being near the superheated line, it was possible to obtain this line itself by an extrapolation from both sides, which might almost be regarded as an interpolation. Reference was made to the measurements of the Thomson-Joule effect in the United States, England, and Czechoslovakia, and the Havlicek apparatus.

Dr. Jakob showed by a mathematical analysis that all that was necessary to determine by experiment as functions of the temperature was α, the supply of heat energy without changing the content, β, the isothermal supply of heat energy and withdrawing of water, and γ, the isothermal supply of heat energy and withdrawing of steam, and if these values were determined in a certain region, it was possible to calculate from them all the thermodynamic properties relating to the saturation region of water and steam with the exception of v' and v" (specific volume of 1 kg. of water and specific volume of 1 kg. of steam, respectively), for which the value of dp/dT along the saturation line was necessary.

The American authors have not given values for the specific heats c' and c" and the specific vol[illegible]

v' and v", the latter being apparently omitted because the saturation line has not been determined in the Bureau of Standards.

Two points were made regarding the heat content of water: (1) At 15° C., ceteris paribus, the Bureau of Standards obtained a value of the enthalpy of water about 0.1 per cent lower than that of Jaeger and Steinwehr, each of the two groups of investigators maintaining that their measurements were accurate to within a few ten-thousandths. (2) The values found by Dieterici seemed to be too high by 0.5 per cent, at most, below 200° C., and too low by 0.8 per cent in the region above 200° C. Fiock corrected the values of Dieterici and reduced them to the Bureau of Standards values. By this, above 200° C., the agreement was as near as 0.2 percent. (Attention is called to the discrepancy in the values of the electrical equivalent of the heat unit, based on the measurements of the Bureau of Standards and of the Reichsanstalt, and the different definitions of these units.)

Direct measurements of the latent heat of steam at higher pressures have, up till the present, not been carried out anywhere in so wide a range

as in the Reichsanstalt: first, up to 180° C. (19 kg. per sq. cm.) by Henning; then, twenty years later, by the same method but with entirely different apparatus, by Jakob up to 210° C. (20 kg. per sq. cm.) and, finally, in cooperation with his assistant, W. Fritz, up to 310° C. (101 kg. per sq. cm.) These latter have recently been working in the region between 101 and 200 kg. per sq. cm. The principal reason why the latent heat was dealt with so thoroughly was that in the most technically important region this heat quantity signifies the greatest part of the enthalpy of steam. At 10 kg. per sq. cm. and 450° C., for instance, the liquid heat was 180, and the energy of superheat 140 kilocalories per kg., whereas the latent heat was 180 kilocalories per kg., that is, 60 per cent of the enthalpy. Even at 100 kg. per sq. cm. and 450° C., the latent heat was still 41 per cent of the enthalpy, being nearly as much as the liquid heat.

The apparatus used by Jakob differed considerably from the American apparatus. The most obvious difference between his calorimeter and that of Osborne was in the dimensions. Whereas the latter was designed for a water content of $\frac{1}{2}$ kg., Jakob's

calorimeter had a capacity ten times as great. Notwithstanding its smaller form, the American apparatus was only suitable up to 50 atm., whereas with Jakob's the experiments could be carried out up to more than 100 atm. without difficulty, and slight alterations suggested in the original text would enable it to be employed up to 200 atm. The total height of Jakob's apparatus was about 1½ m.

The fundamental equation of the method used by Jakob was given in the original text, and permitted the calculation of the latent heat, r, in two ways. Both methods of calculation were used, but instead of starting from only two or three tests, each giving an equation referring to another mass, m., Jakob and his associates always treated all experiments belonging to a certain temperature together, by the method of least squares. Certain further corrections were indicated. A graph in the original text ranging to 250° C. and 40.5 kg. per sq. cm. pressure was given to show how closely the difference series of the German experiments connect with one another. Up to 56 kg. per sq. cm. the difference between the Osborne and the Jakob values was always less than 0.2 per cent.

Steam research can be approached through regions of physics which seem to lie off the main path, one such way being by the acoustic phenomenon of sound velocity. At this point, however, Dr. Jakob dealt more in detail with modern optical methods based on the employment of theories concerning the behavior of the atoms in the molecule. In this kind of work the gram-molecule was used as a unit of weight and denoted a a mol. The methods of calculation of the energy of rotation of a diatomic and triatomic molecule were presented, and the difficulties involved were briefly stated.

Spectroscopy was mentioned as a method by which, from the place of the spectral lines in the spectrum, one could exactly determine the frequencies. This opened the possibility of determining by means of spectroscopic measurements that part of the specific heat which was not obtainable by the classical theory of molecules. As in all problems of spectroscopy, the question consisted (1) in obtaining clear and distinct lines, and (2) in interpreting them in a right manner. Neither condition was easy to fulfil.

The difficulties as regards the so-called "polar" or "heteropolar" molecules such as those of water consisted

in fact that the spectra in question lay far in the ultra-red and could not be fixed by ordinary photographic plates; further, they possessed a very great number of lines, and the fundamental vibration was difficult to determine; finally, there existed also optically inactive vibrations. Jakob tells how a way out of these difficulties was opened up by the use of the so-called Raman effect.

In comparing the results of the spectroscopic and calorimetric methods, with reference to diatomic gases, Jakob stated that the spectroscopic method had already succeeded in determining the variation of the specific heat with the temperature probably more exactly than other methods, and that, regarding steam, results seemed quite close at this point. This, however, held good only for atmospheric pressure. It seemed to be of decisive importance to have a full knowledge of the polymerization, or, as Professor Callendar called it, coaggregation of the molecules. The Callendar theory was published in 1900 and was restated by Jakob in his lecture. Callendar based his calculations on the value of $c_{p0} = \frac{13}{9} R$, where R is the special gas constant for steam. From measurements made in Munich, it was found that even

at moderate temperatures c_{p0} was not constant but increased with the temperature. This Jakob considered as one of the weakest points in Callendar's system, though justified by expediency.

Jakob pointed out a minor defect of the Callendar system dealing with Callendar's expressions for v, and then proceeded to the consideration of Callendar's hypothesis that in each volume of water the same volume of steam was dissolved. From this hypothesis he obtained:

$$i' = c_i t + \frac{v'}{v'' - v'} r$$

Since this equation seemed never to have been rigidly derived, Dr. Jakob proceeded to give a derivation. He assumed an ideal liquid, differing from real water only by the singularity that no steam be dissolved in it, and that its specific heat be denoted by c_i, where c_i signifies the well known minimum value of the specific heat of water. He suggested that 1 kg. of real water, with the specific volume v', originated in the following way: the volume v' might originally be filled by ideal water, and then the same volume of steam, that is, v'/v" kg. of steam be dissolved in it. To produce this mass of steam, the heat quantity

$(v'/v'')r_i$ would be necessary where r_i signified the latent heat of ideal water. Since, after this a part of the real water consisted of dissolved steam, the evaporation of 1 kg. of real water required only the heat quantity:

$$r = r_i - \frac{v'}{v''} r_i = \frac{v'' - v'}{v''} r_i$$

from which it immediately followed that

$$r_i = \frac{v''}{v'' - v'} r$$

Now, according to Callendar's hypothesis, the enthalpy of real water was

$$i' = c_i t + \frac{v'}{v''} r_i$$

And substituting r_i from the preceding equation, Callendar's starting equation was obtained:

$$i' = c_i t + \frac{v'}{v'' - v'} r$$

Substituting in this equation, according to the formula of Clapeyron-Clausius,

$$\frac{r}{v'' - v'} = \frac{1}{J} T \frac{dp}{dT}$$

be obtained

$$i' = c_i t + \frac{1}{J} v' T \frac{dp}{dT}$$

He stated that it was remarkable, but had apparently been forgotten that Callendar started originally from this

equation, established as early as 1889 by J. M. Gray, and adopted in the year 1902 by Callendar, and that the suggestion of the "ideal water", on which Gray based his equation, was originated earlier by Rankine. In developing the above equations, Callendar finally obtained an equation for the saturation pressure, and Jakob brought out that the saturation pressures calculated according to this formula deviated from the best-known experimental values by less than $\pm$ 1 percent in the region from 200 to 374° C. This was an astonishingly good result considering the way in which it was obtained. However, Callendar's theory did not correspond entirely to reality, since as shown in the original text, the best experimental values agreed at least by 0.1 to 0.2 percent.

Jakob mentioned that the equation of the saturation pressure (44 in the original) was said to hold good even beyond 374° C., up to the extraordinary temperature of 380.5° C. On the contrary, the equations of the enthalpy and of the specific volume (28 and 29) were said to fail at the saturation limit from 374° to 380.5° C. If Jakob understood Callendar in this respect, these equations gave only the specific volume of steam when separated from the water by a meniscus.

But beyond 374° C., instead of the meniscus a horizontal separation line existed, which Callendar called a "demarcation line," and the medium under consideration was not water and steam, but two water-steam mixtures. Below 374° C. (225 kg. per sq.cm.) water and steam were described as mixtures of molecules of different complexity. The water molecules decreased in complexity with increasing temperature, whereas the number of complex molecules in the vapor increased with rising pressure. At pressures beyond 225 kg. per sq. cm., the molecules in the part occupied by steam became still more coaggregated and at the same time less in number, and since, according to Callendar's hypothesis, as many steam molecules were always dissolved in the water as existed in the same volume of steam in equilibrium with the water, the numbers of steam molecules also, still present in the water, continually decreased until ultimately at 380.5° C., all steam molecules were condensed and the mixture had taken on the properties of water. It is just this hypothesis of the equality of the dissolved steam volume with the water volume, which led most naturally to the relations

$$v'' = v', \qquad i'' = i', \qquad \text{and } r = 0$$

Which signify that now there existed no longer any difference between the steam of highest complexity and the water.

This is a theoretical corroboration of the suggestion, appearing rather arbitrary on first sight, that exactly as many molecules of steam should be dissolved as exist in the same steam volume. Another explanation of this suggestion was formerly given by interpreting the water surface as a film semi-permeable to steam molecules.

Jakob says in Mechanical Engineering, May 1932, "That only the newest Table, that of Keenan, of 1930 remains always inside the Tolerance." (International skeleton Table.)

Each steam table author, in preparing his tables, started from such properties of steam as seemed to him particularly suited for this purpose, as determined by series of experiments. These values were reproduced by empirical formulae from these, using other known properties as laws, the remaining properties were calculated. The two points kept in mind were (1) Latent heat of evaporation at critical point = 0,(2) Consistency of the results with their own and those of other workers.

To quote from Mr. Keenan, Assistant Professor Mechanical Engineering, Stevens Institute of Technology, "The recent world wide research has revealed the characteristics of superheated steam throughout wide ranges of pressure and temperature which the older steam tables

had covered by intelligent guesses and ingenious speculations."

The article of which this quotation was the opening paragraph went on to give a very interesting report of tests made by the Special Research Committee on Thermal Properties of Steam on the Thermal Properties of Compressed Liquid Water. This report has been used freely by the author of this Thesis in the drawing of the properties of the subcooled liquid region.

THEORETICAL DISCUSSION

General Equations of Thermodynamics

Practically all changes in the state of a medium occur accompanied by heat transition. The rate of adding or rejecting this heat is called by such an eminent authority as Goodenough, thermal capacity. More prominent among these capacities are: $(\partial q/\partial t)_v$, specific heat at constant volume, usually shortened to c_v; $(\partial q/\partial t)_p$, specific heat at constant pressure, usually shortened to c_p; $(\partial q/\partial v)_t$, latent heat of expansion, usually shortened to l_v; and $(\partial q/\partial p)_t$, expressed by l_p. It may be called to point, that since heat added is not a state function, these relations are merely rates and are not in any sense, partial derivities of the function of the medium.

It may be shown that the following equations are true for any medium:

(1) $dq = (\partial q/\partial v)_t dv + (\partial q/\partial t)_v dt$

(2) $dq = (\partial q/\partial t)_p dt + (\partial q/\partial p)_t dp$

(3) $dq = (\partial q/\partial p)_v dp + (\partial q/\partial v)_p dv$

Substituting the above symbols for the capacities, we have

(4) $dq = l_v\, dv + c_v dt$,

(5) $dq = l_p\, dp + c_p dt$

and from the characteristic equation of the medium

in question,

$$v = f(t,p),$$

we may write

(6) $dv = \partial v/\partial t \; dt + \partial v/\partial p \; dp.$

We may write the First Law of Thermodynamics as follows:

(7) $dq = du + Ap \; dv$

and the Second Law of Thermodynamics, as follows:

(8) $dq = T \; ds$

A third thermal property, called Enthalpy, may be introduced with the relation:

(9) $h = u + Apv$

which by differentiation is

(10) $dh = du + A \; p \; dv + A \; v \; dp$

which may reduce to

(11) $dh = dq + A \; v \; dp$

Note that for a constant pressure process we have $dh = dq$ and for a frictionless adiabatic we have $dh = A \; v \; dp$.

By combining (5) and (11) we have

(12) $Dh = (l_p + A \; v) \; dp + c_p \; dt$

and by combining (5) and (8) we have

(13) $ds = l_p/T \; dp + c_p/T \; dT$

Since both h and s are state functions, the differentials are exact and the coefficients are partial derivitives, so that

(14) $l_p + A\,v = \left(\frac{dh}{dp}\right)_t$; and $c_p = \left(\frac{dh}{dT}\right)_p$, and

(15) $l_p/T = \left(\frac{ds}{dp}\right)_t$, and $c_p/T = \left(\frac{ds}{dT}\right)_p$

Then from (14)

(16) $\frac{d\ l_p}{dT} + A\frac{dv}{dT} = \frac{d\ c_p}{dp}$

And from (15)

(17) $\frac{dl_p}{dT} - \frac{l_p}{T} = \frac{d\ c_p}{dp}$

Combining (16) and (17)

(18) $\frac{l_p}{T} = - A \frac{dv}{dT}$

Then from (18) we obtain

(19) $\left(\frac{dc_p}{dp}\right)_t = - AT \left(\frac{d^2v}{dT^2}\right)_p$.

This is one of the fundamental equations proposed by Professor G. A. Goodenough in "Principles of Thermodynamics."

This equation has been used with suitable constants to complete very comprehensive and satisfactory determination of specific heats for superheated steam.

This equation has the form

(20) $\left(\frac{dc_p}{dp}\right)_T = (1 + 3\ ap^{\frac{1}{2}}) \frac{Amn(n+1)}{T^{(n+1)}}$ which, upon integration is

(21) $c_p = p(1 + 2ap^{\frac{1}{2}}) \frac{Amn(n+1)}{T^{(n+1)}} + \phi(T)$

This function ϕ (T) must be determined by experiment as well as the constants a, m, and n. This function has the form $a + bT + fT^2$. Then the specific heat at constant pressure is a function of pressure and temperature.

Using these and other formulae which were built up from the pure mathematics of Thermodynamics, Dr. Goudenough computed values of the properties of both steam and ammonia. The constants were, of course, supplied by experimentation. An example taken from the work of Knoblauch, Linde and Kleve, which was until the recent investigation of the Steam Table Conference the most reliable on the specific volume of saturated and superheated steam, is:

$$(22)\quad v - c = \frac{BT}{p} - (1 + 3ap^{\frac{1}{2}})\frac{m}{T^n}$$

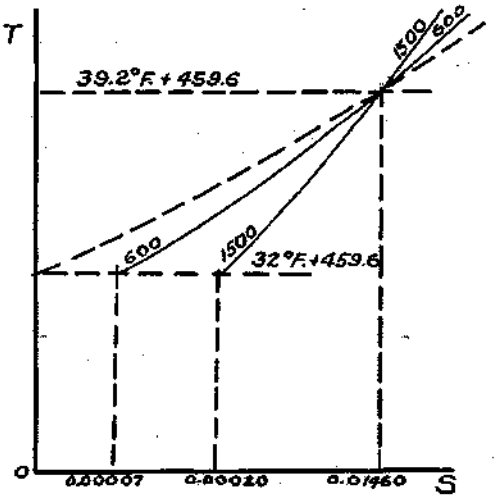
Sub-cooled Water Region

Behavior of constant temperature lines in the sub-cooled water region is of peculiar moment because temperature characteristics in this region are only of recent development. As far as the author can determine, this has never been charted for practical use previous to this work. Due to the energy quantity often called external work or pump work being added as low temperature water is raised to higher pressures, the enthalpy is increased and at higher pressures gives enthalpy values much in excess of the saturated water enthalpies, which have been previously used instead. As higher temperature water is compressed, the increase is much less until at a temperature of 500° F. the isotherm is

one of practically constant enthalpy and at higher temperatures shows a marked decrease in enthalpy with compression.

By the equation for enthalpy, $H = E + \frac{PV}{J}$, we can see the reason for this as the value of E is practically constant for isothermal changes at low temperatures. However, it has become evident that E is not a function of temperature at higher temperatures, so that H has smaller values as $\frac{PV}{J}$ increases.

It is interesting to note the crossing of the saturation line at 39.2 F, the point of maximum density. This state is not shown by Charts but by attached figure as in article by Julian C. Smallwood, in Mechanical Engineering October 1931, Vol.53, Page 716, "Thermodynamics of High Pressure Water."



The maximum enthalpy for 550 pounds per square inch saturated vapor is explained by the theory that when water vapor is formed by the combustion of hydrogen

gas supported by oxygen gas, the molecules of H_2O are each a complete unit held apart by a certain force. When energy is taken away, these attraction and repulsions vary and the molecules group themselves into $(H_2O)_2$, $(H_2O)_3$ etc. When these molecules are again heated at different temperatures and with different corresponding pressures being exerted, the values of the energy required vary and since these energy values compose the enthalpy values, the resulting variation as charted shows up with an increasing enthalpy of saturated vapor from low pressures up to about 550 pounds per square inch and then decreasing up to the critical point.

It has been practice to apply the perfect gas laws to very high superheated vapor of high pressures and to all superheated vapor of low pressures. This practice has been especially handy in the computations of low pressure vapor as present in the atmosphere. At pressures lower than those shown in existing commercially published steam tables for superheated vapor, it has been the practice to take the saturated temperature which would correspond to the superheat temperature of the vapor and assume that the constant temperature and constant enthalpy exist

in step as in gases. This method has resulted in marked accuracy. The Charts presented herewith have been extended into the lower pressure regions so that the enthalpies may be read directly from the Chart for superheat temperatures of low pressures.

METHODS USED IN DEVELOPMENT

The Charts which the author presents herewith is not set forth as a new idea. The same kind of a chart is widely used in refrigeration for the various refrigerants. A similar chart was prepared by Mollier and others as late as 1904, though this one could not pretend to cover as large a range of values as the one presented herewith. The main value of this Chart over many others is the presence of very satisfactory constant volume lines as well as the lines of constant entropy, quality, pressure and temperature. W. S. Huntington used this type of chart for a restricted region in his book "Graphic Thermodynamics" in developing his Heat-Work Diagrams.

The Pressure-Enthalpy Charts for Water and its vapor, Steam, as here presented have been prepared after reference to many sources. Those which have been previously presented were for a limited region, due to lack of adequate research. These Charts cover as much of the regions as is at present known, the saturated water line, sub-cooled water region, wet vapor, or the region of the mixture of water and its vapor, the saturated vapor line and the superheated vapor region, both high and low pressure. No attempt has been made to include any information concerning the very unstable and consequently little known and practically un-investigated state of super-saturated vapor. (However, the values as found on these Charts

may be used in the formulae proposed by several texts for super-saturated steam calculations. See any standard text that treats this phenomenon.)

The plotting was done on 14 plates using Semi-Logarithmic cross-section paper of three cycles. Arrangement of plates has been such that remarkably good characteristics for continuity of process exist.

Sub-Cooled Water

The data used in plotting in the sub-cooled water region was found in Table 1 Compressed Liquid, in article by Professor Joseph H. Keenan, on "Thermal Properties of Compressed Liquid Water." Volume 53, Page 130 Mechanical Engineering. By interpolation and some extrapolation the lines of constant temperature and constant entropy were laid out. The specific volume data was not sufficient to plot nor was there enough variance from the saturated water volumes for any difference in results in engineering calculations. For specific volumes of saturated water, Keenan's Steam Tables are recommended as the best source.

Steam Dome

The Steam Dome is bounded by the saturation curve for liquid and the saturation curve for steam. These have been plotted from values shown in Keenan's

"Steam Tables" which as shown in previous sections have been accepted as well within the tolerances of the International Steam Research Committee.

The properties of quality, volume and entropy within the dome have been computed as follows:

The locus of any quality, x, may be found by plotting the enthalpy, H, resulting from the use of that quality in the formula, $H = h_f + (x)(hfg)$ against the pressure corresponding to the values hf and hfg.

The locus of any volume, v, may be found by plotting the enthalpy, H, resulting from the use of a quality, x, in the formula, $H = hf + (x)(hfg)$ against the corresponding pressure when the quality is determined by the formula

$$x = \frac{V - vf}{vfg}$$

The locus of any entropy, S, may be found by plotting the enthalpy, H, resulting from the use of a quality, x, in the formula, $H = hf + (x)(hfg)$ against the corresponding pressure when the quality is determined by the formula $x = \frac{S - sf}{sfg}$

Superheated Steam

The properties of temperature, volume and entropy within the superheated region were plotted from values found in Keenan's Steam Tables. Even values of volume and entropy were found by straight line interpolations. Temperatures, intermediate of values given in the Keenan Tables, were plotted by straight line interpolations.

USES OF CHARTS

These Charts are constructed to show properties of one pound of water or its vapor. Any property, such as enthalpy, entropy, volume, may be found for a fraction of a pound or any multiple of a pound by the proper process of division or multiplication of the specific (per pound) value: i.e. the enthalpy of water at 1000 lbs./ square inch and 500°F. is shown on Plate #11 as 487.4 b.t.u. Then 0.25 pound of water has an enthalpy of (0.25)(487.4)= 121.8 b.t.u.

Constant Pressure

Example 1. One pound of water at a pressure of 1000 lbs. / square inch and a temperature of 100° F. is heated at constant pressure to 600° F. It is desired to determine heat added. Refer to Skeleton Chart, Plate #1. Initial state indicated as "A" is on Plate #9 at intersection of 1000 lbs. / square inch and 100° F., which has an enthalpy, H_1 = 70.5 b.t.u. The final state, indicated as "B", is on Plate #14 at intersection of 1000 lbs. / square inch and 600° F. which has an enthalpy, H_2 = 1248.7 b.t.u. Then the heat added, $Q = H_2 - H_1$ = 1248.7 - 70.5 = 1178.2 b.t.u. By use of steam tables and assuming a constant enthalpy for all pressures of isothermal water, the computations would be 1248.7-68 = 1180.7 b.t.u., an error of 2.5 b.t.u.

Constant Volume

Example 2. One pound of steam confined in a tank at a temperature of 700° F. and a pressure of 500 lbs. / square inch is cooled until the pressure becomes atmospheric. It is desired to determine the heat abstracted. Refer to Skeleton Chart, Plate #1. Initial state is indicated as "C" and is found on Plate #14. The volume is 1.3 cu.ft. and the enthalpy, 1357 b.t.u. The final state is indicated as "D" on Plate #9 with volume, 1.3 cu.ft. and enthalpy, 227.5 b.t.u. Then the heat abstracted,

$$Q = U_1 - U_2 = H_1 - H_2 - \frac{v(P_1-P_2}{J}$$

$$= 1357 - 227.5 - \frac{(1.3)(144)(485.3)}{778} = 1012.7 \text{ b.t.u.}$$

Throttling Process

The solution of problems of throttling water and steam are especially facilitated by these Charts. NO CHART IS IN USE AT PRESENT as far as the author can determine which offers a GRAPHICAL SOLUTION OF THROTTLING OF WATER.

Example 3. Throttling of Water:-One pound of water at a temperature of 400° F. and a pressure of 400 lbs. / square inch is throttled to a pressure of 14.7 lbs. / square inch. It is desired to determine the final condition of the medium. The initial state is located on Plate #10 (at E) and the enthalpy is read as 371.0 b.t.u. The constant enthalpy line (throttling is always assumed as constant enthalpy) is followed to the pressure of 14.7 lbs. / square inch (atmospheric

pressure) where the state is found to be a mixture of water and steam (at F), with an entropy of).596 and a quality).196. That is, 19.6 per cent of the medium is steam and 80.4 per cent is water. The volume is read as 5.3 cu.ft. / pound.

Example 4. Throttling of Steam:-One pound of steam of unknown quality is throttled from 100 lbs. / square inch to a pressure of 14.7 lbs. / square inch and a temperature of 240° F. The final condition is found (at G on Skeleton Chart, Plate #1) on Plate #13 with an enthalpy of 1163.5 b.t.u. Following the constant enthalpy line to the intersection with 100 lbs. / square inch line, a quality of 97.4 per cent and a volume of 4.3 cu.ft. is found.

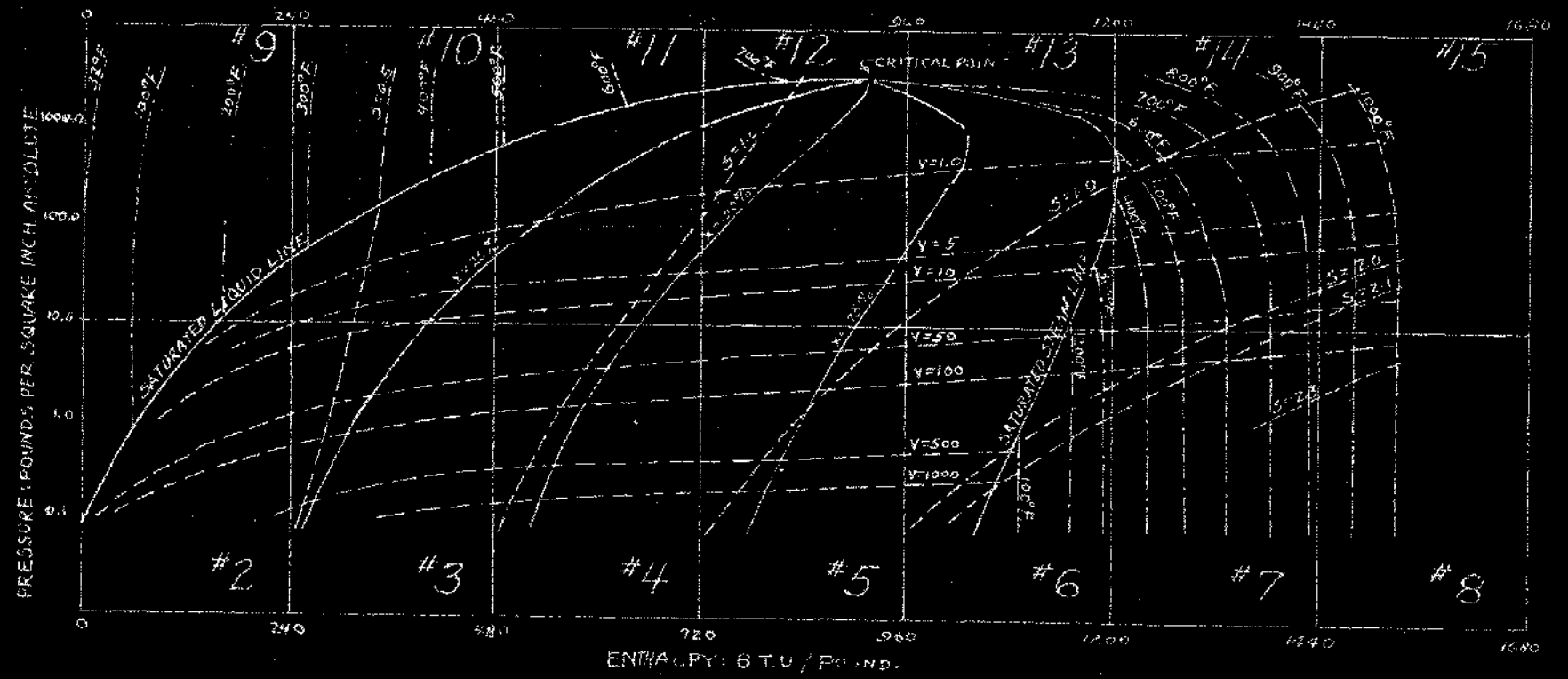
Factor of Evaporation.

Example 5. A power plant is using feed water delivered to the boiler at a temperature of 100° F. and a pressure of 600 lbs. / square inch. The boiler generates steam at a pressure of 450 lbs. / square inch and a temperature of 750° F. The enthalpy of the water supplied is found on Plate #9 (J on Plate #1) as 73.5 b.t.u. The enthalpy of the steam generated is found on Plate #14 (K on Plate #1) as 1388.5 b.t.u. Then by the formula for Factor of Evaporation, we have

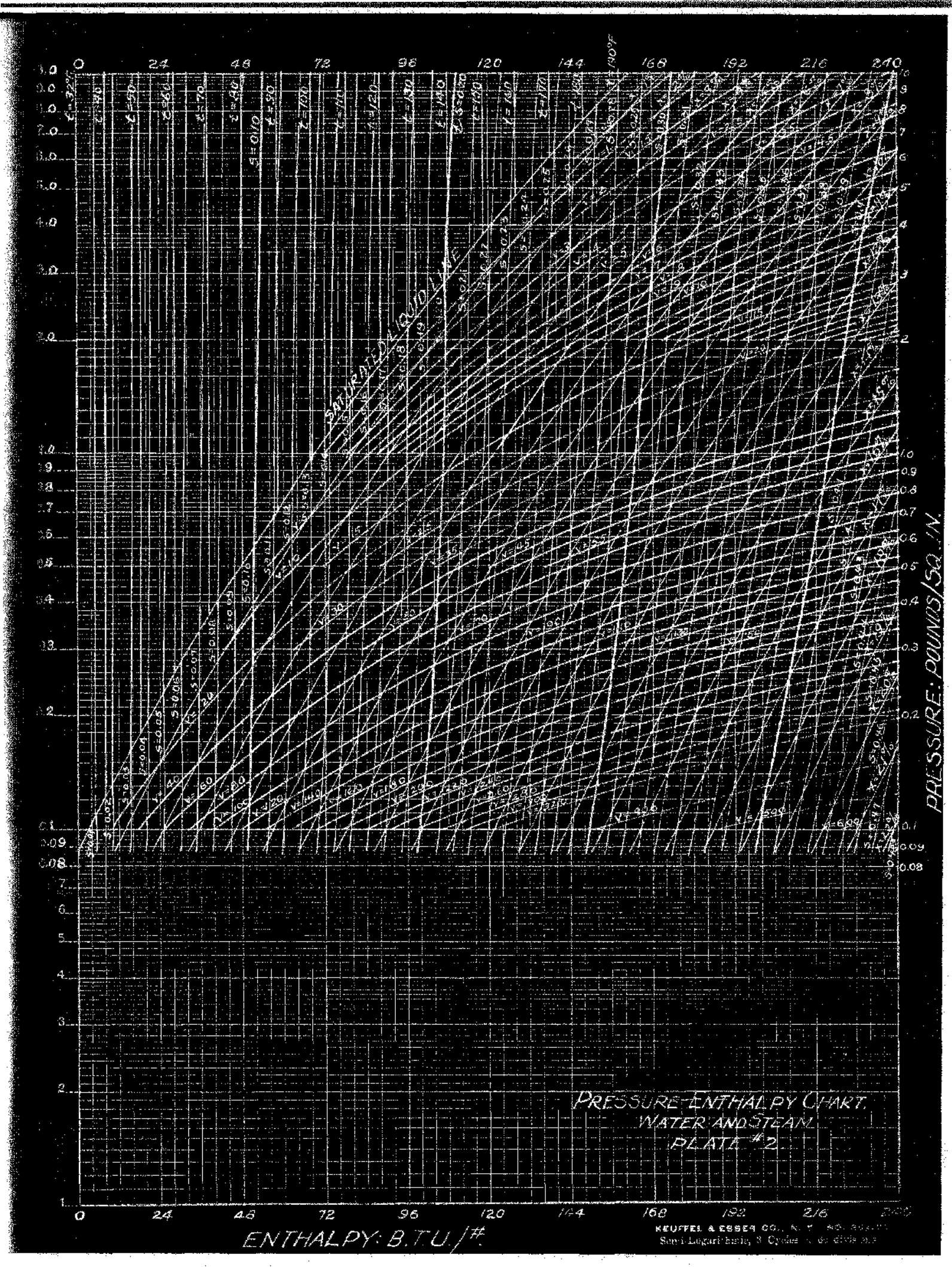
$$F = \frac{H_1 - H_2}{970.2} = \frac{1388.5 - 73.5}{970.2} = \frac{1315}{970.2} = 1.355$$

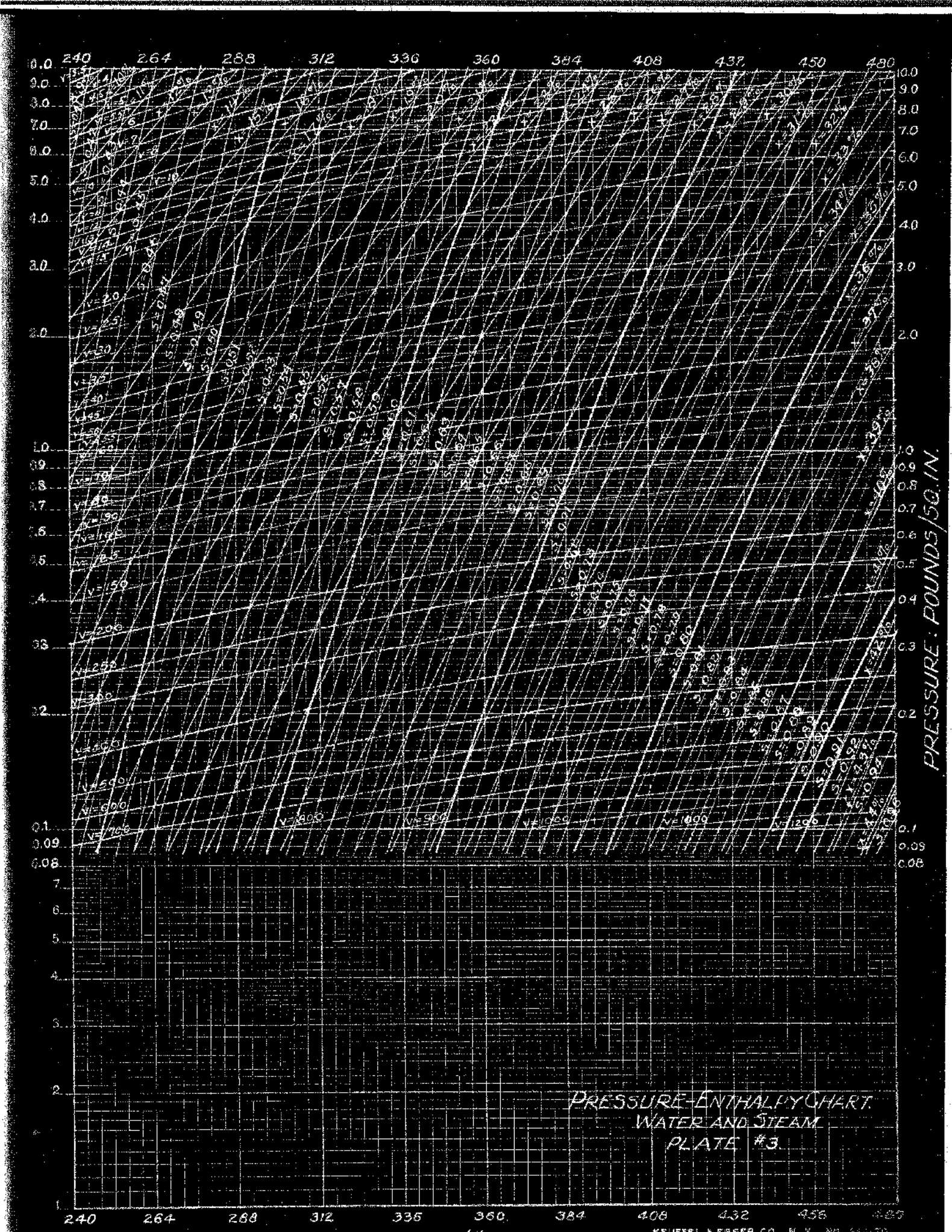
This factor is an important tool in the determination of capacities of power plants.

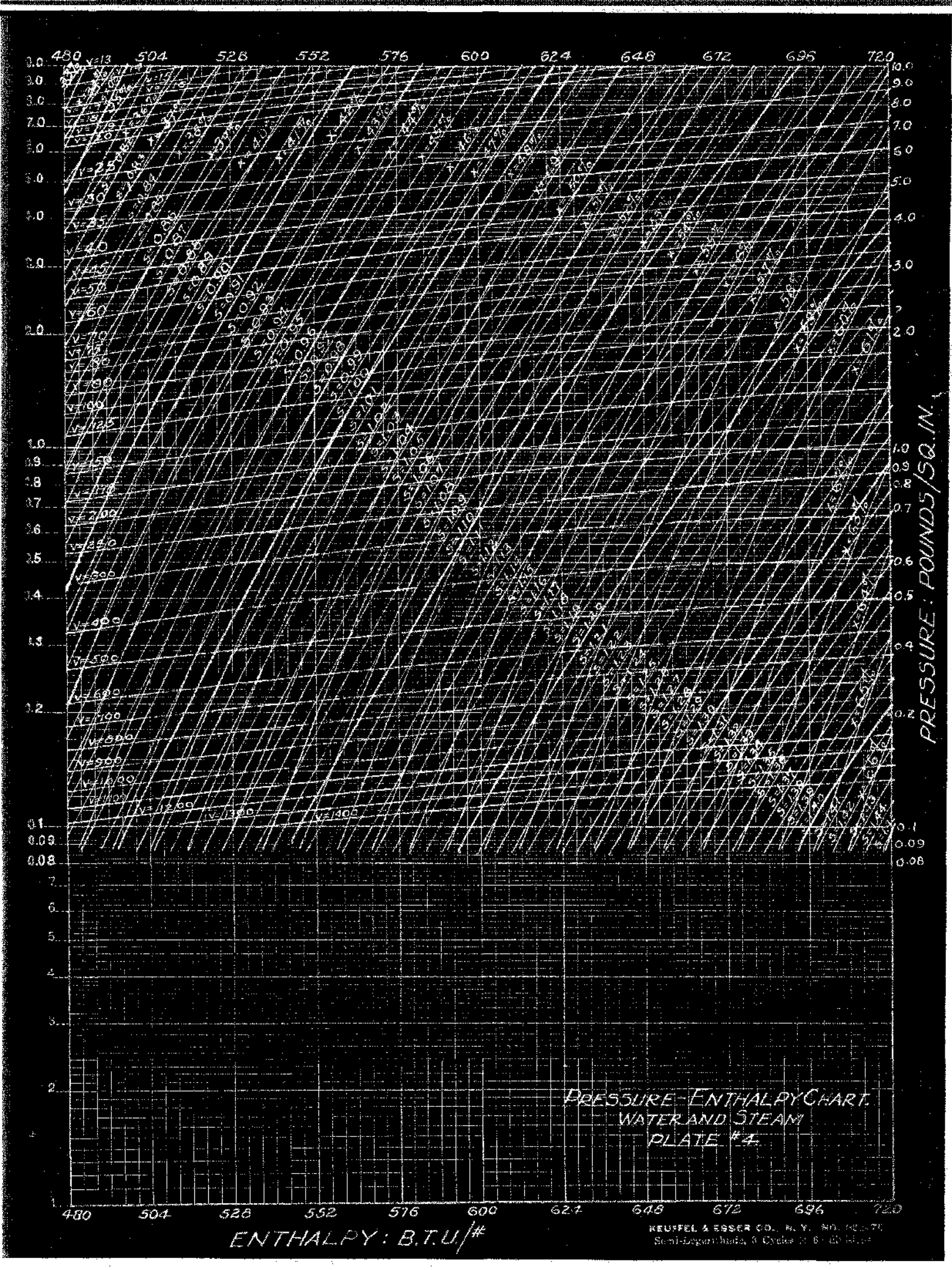
Many other computations performed by use of other charts can be computed with equal facility on these Charts. Among these are: computations of Rankin cycle efficiencies, steam turbine calculations, adiabatic compressions and expansions, and other computations.

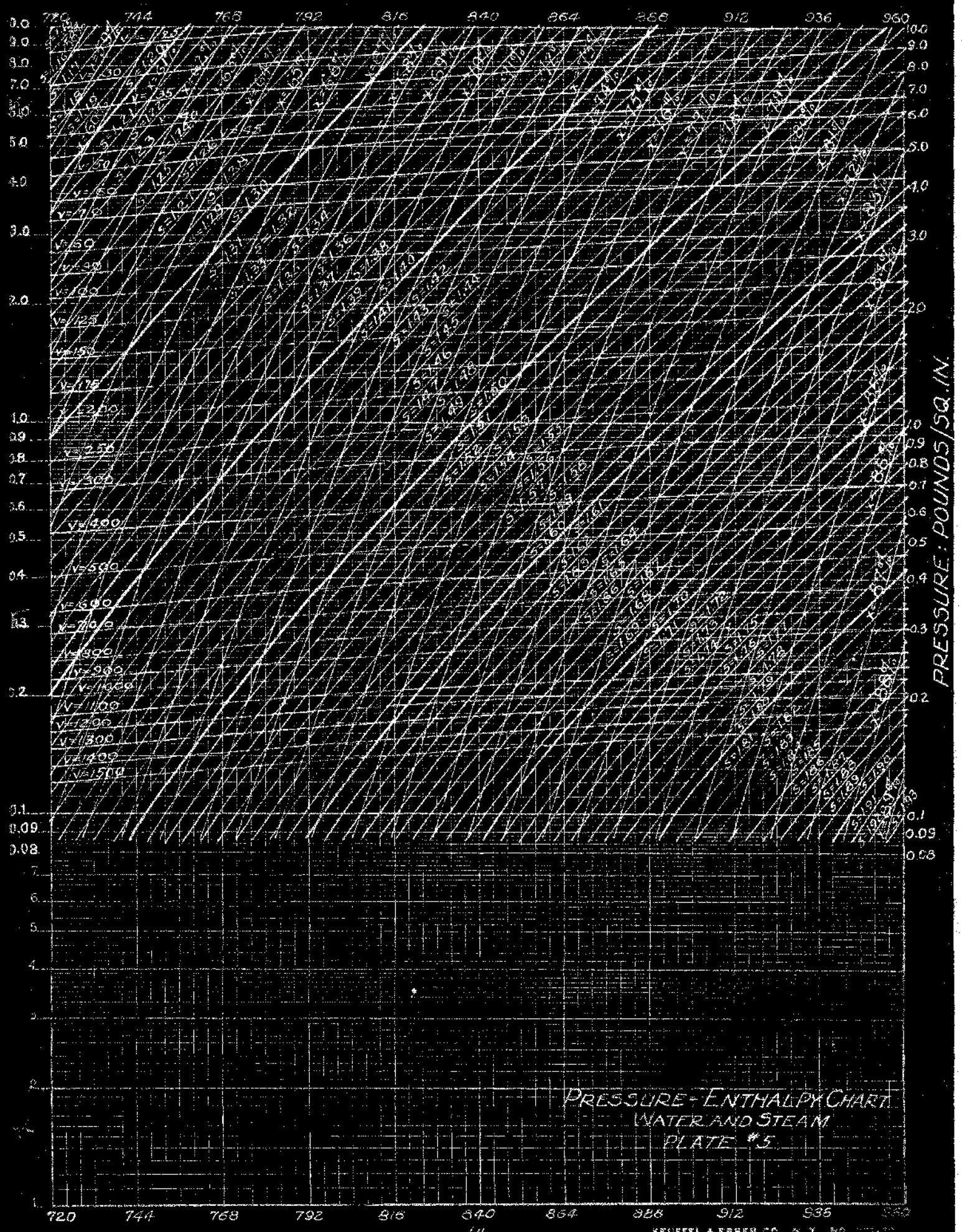


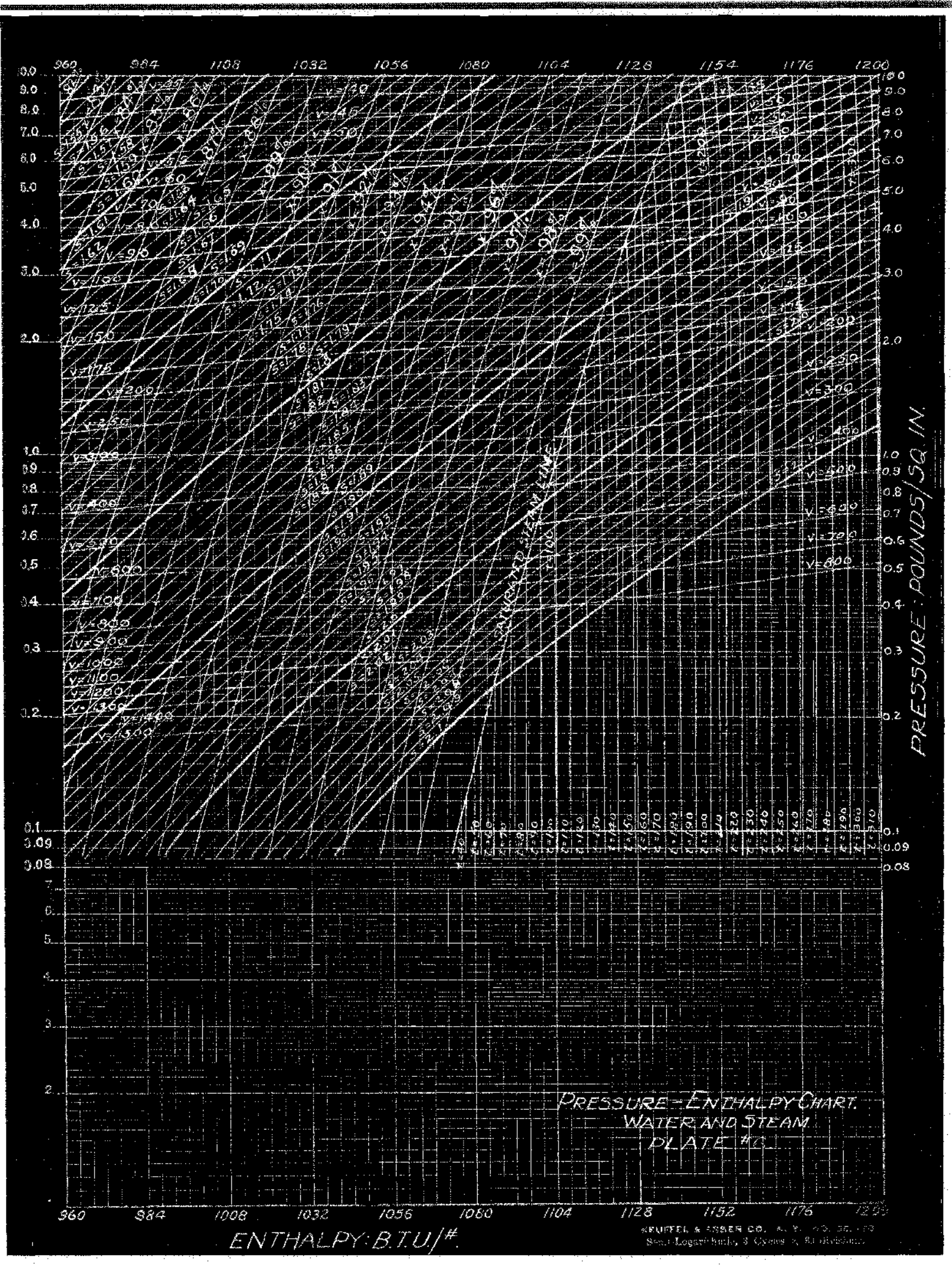
SKELETON CHART
OF
PRESSURE-ENTHALPY
WATER AND STEAM
PLATE #1.

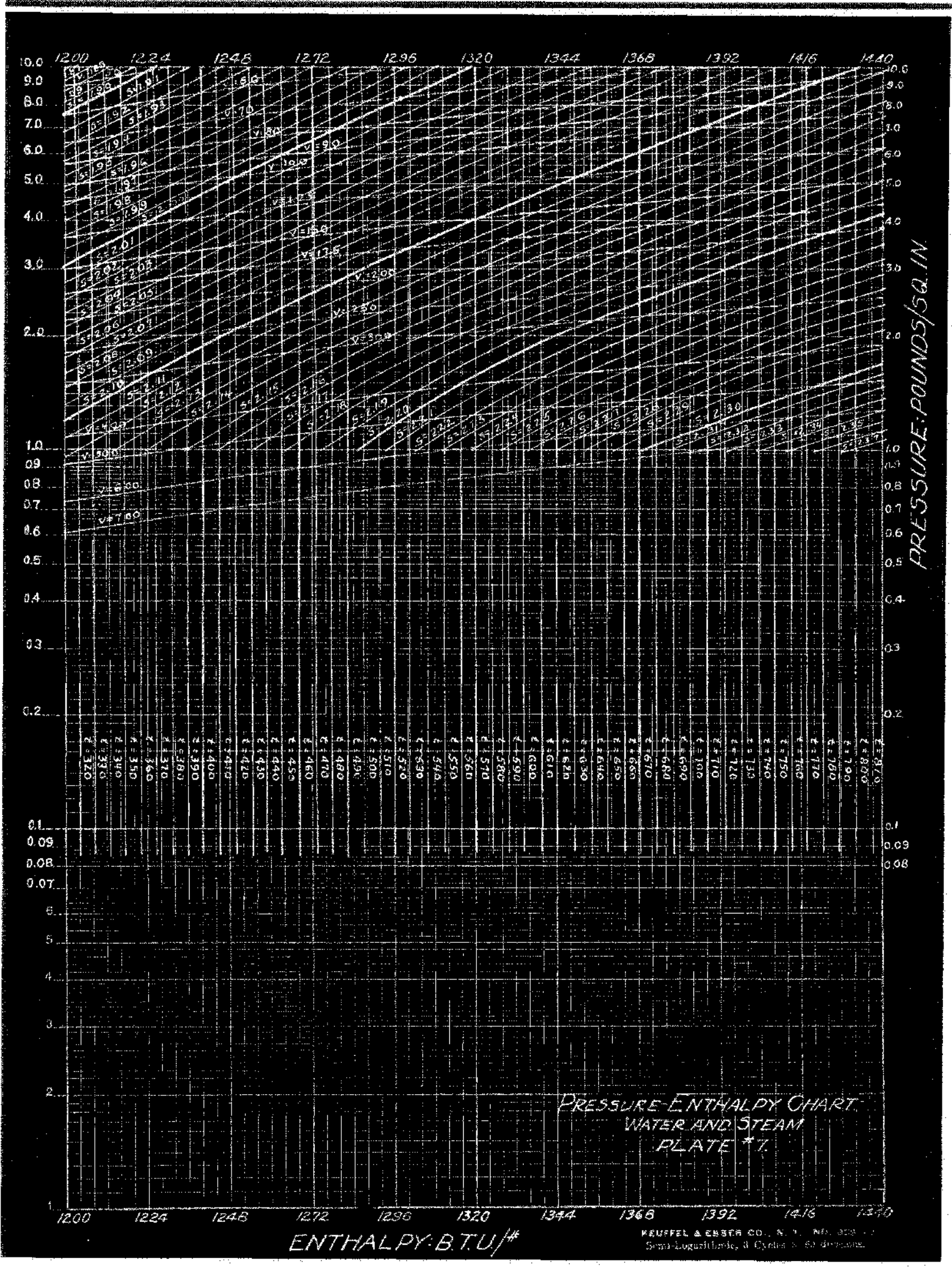

PRESSURE-ENTHALPY CHART.
WATER AND STEAM.
PLATE #2.
ENTHALPY: B.T.U./#.
PRESSURE: POUNDS/SQ. IN.
SATURATED LIQUID LINE
KEUFFEL & ESSER CO.
Semi-Logarithmic, 3 Cycles

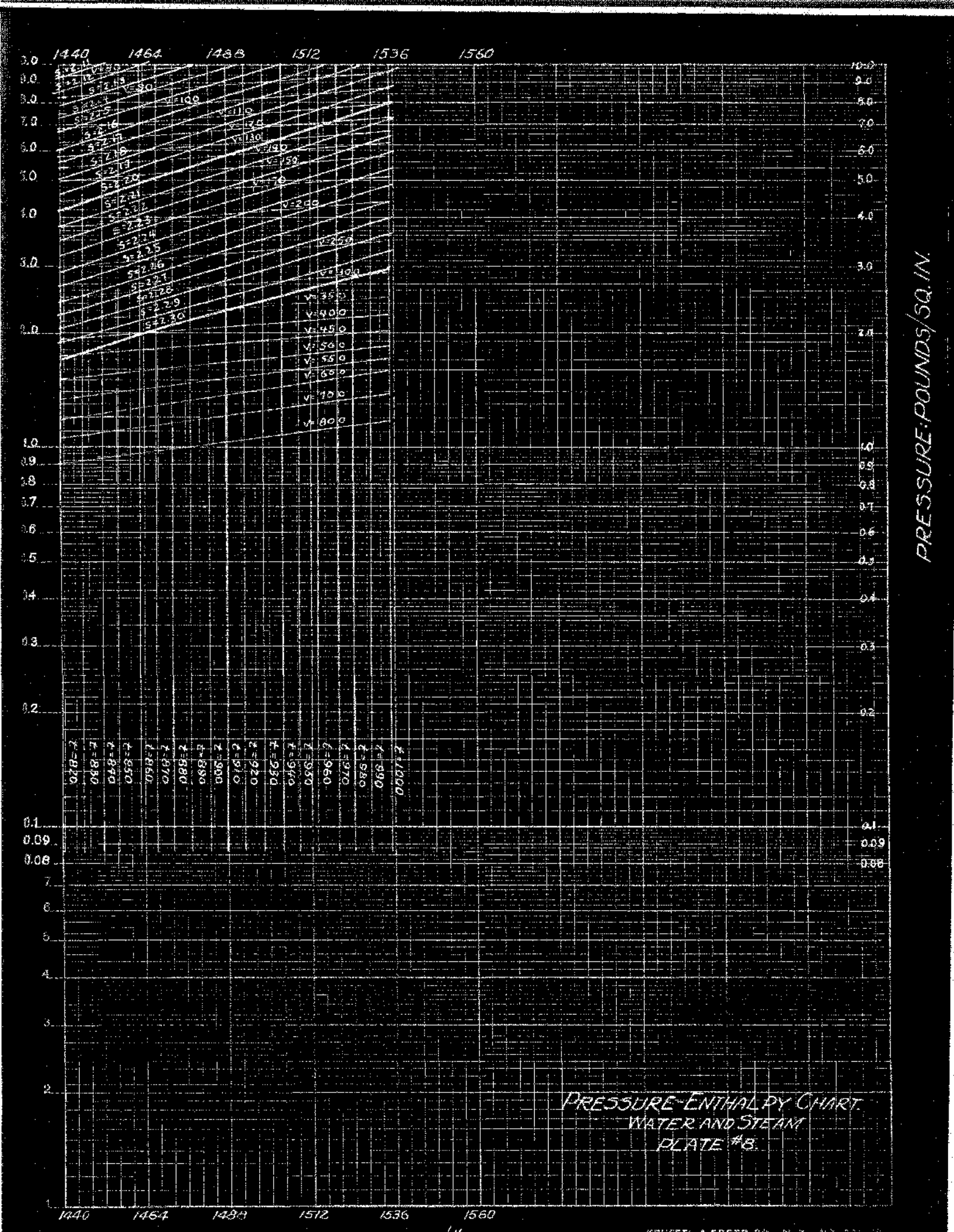

PRESSURE-ENTHALPY CHART.
WATER AND STEAM.
PLATE #3.
ENTHALPY : B.T.U./#
PRESSURE : POUNDS/SQ. IN.
KEUFFEL & ESSER CO.
Semi-Logarithmic, 3 Cycles

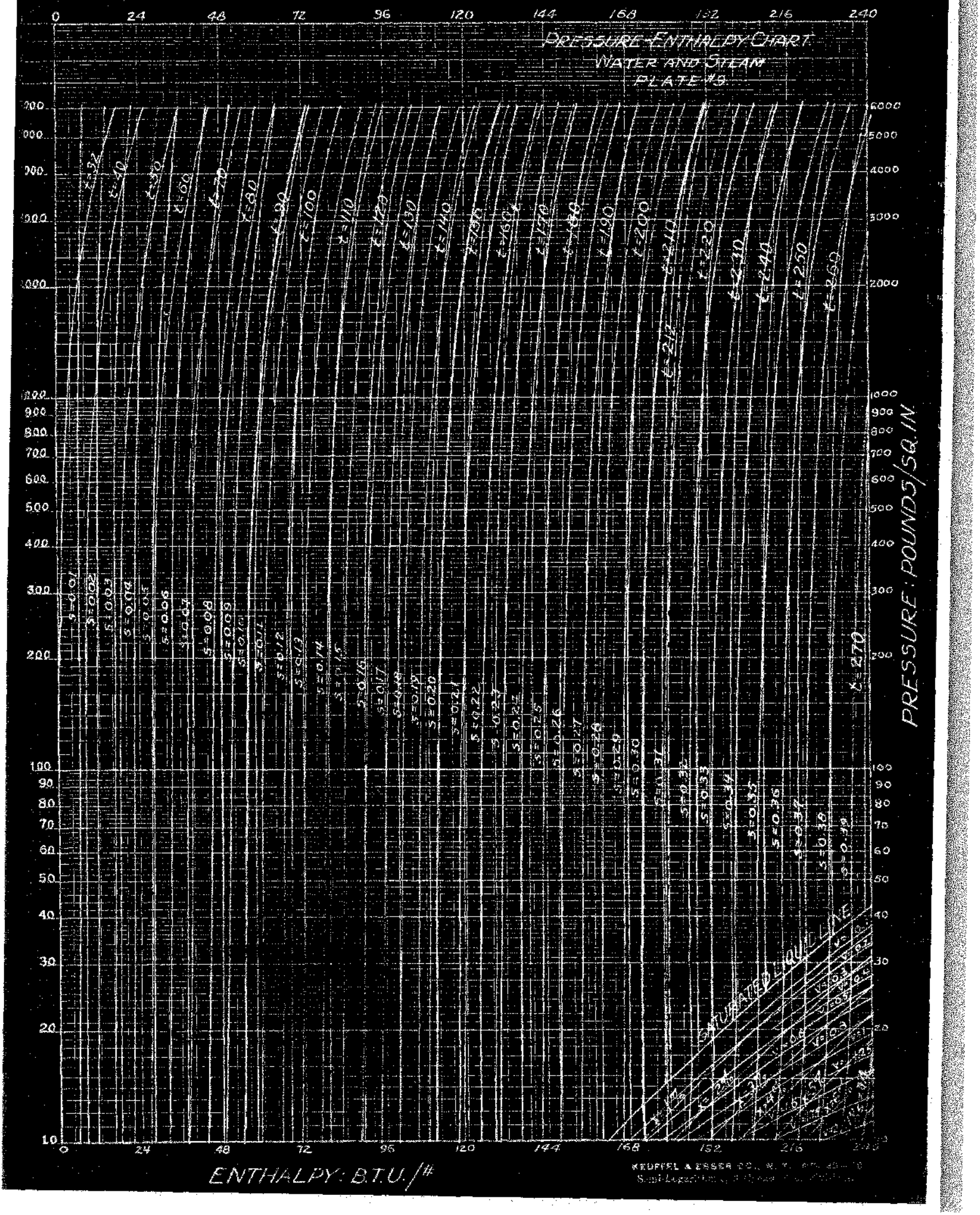

480
504
528
552
576
600
624
648
672
696
720
PRESSURE: POUNDS/SQ. IN.
ENTHALPY: B.T.U./#
PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #4.
REUFFEL & ESSER CO., N. Y.

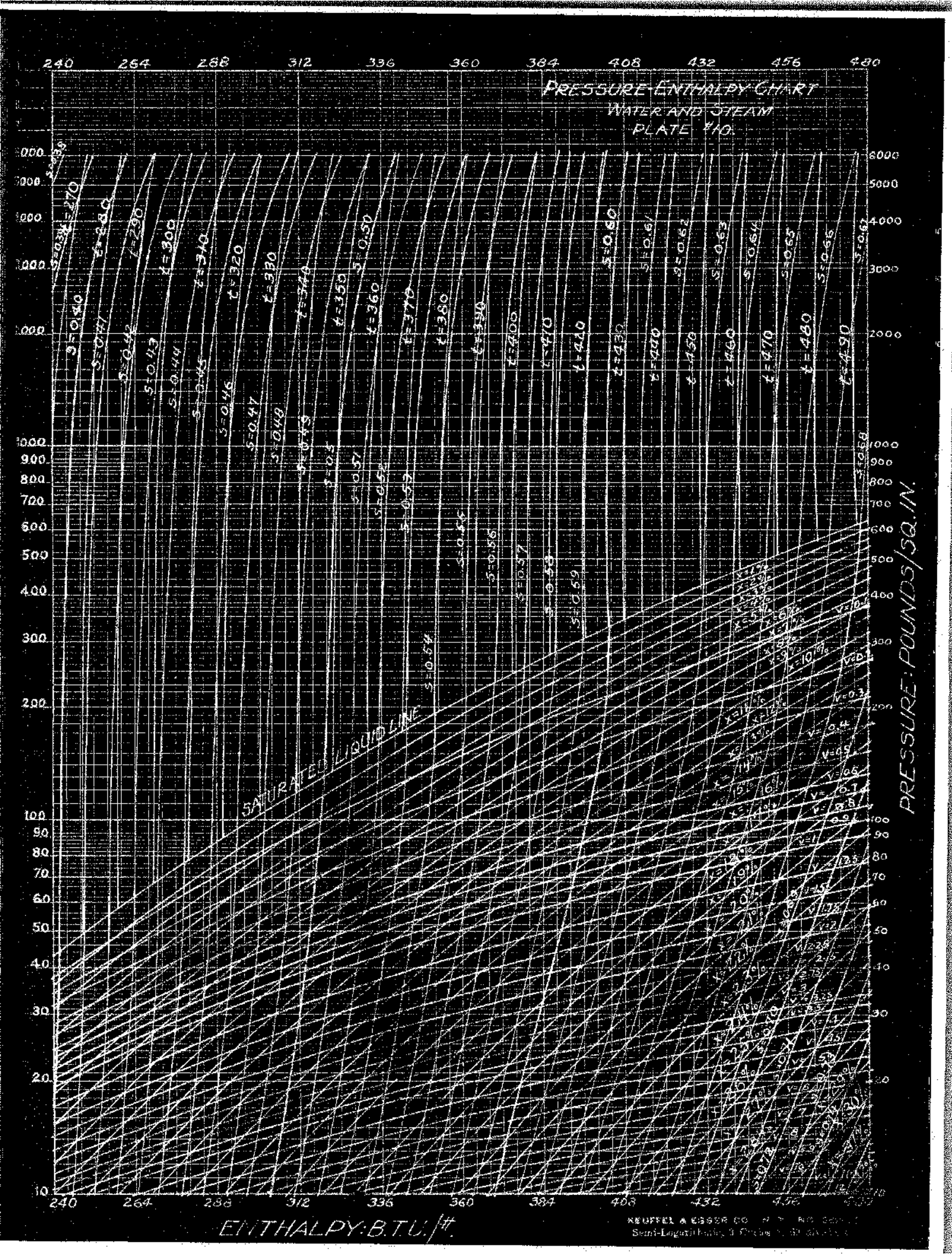

720
744
768
792
816
840
864
888
912
936
960
ENTHALPY: B.T.U/#
PRESSURE: POUNDS/SQ.IN.
PRESSURE - ENTHALPY CHART
WATER AND STEAM
PLATE #5
KEUFFEL & ESSER CO., N. Y.
Semi-Logarithmic, 3 Cycles

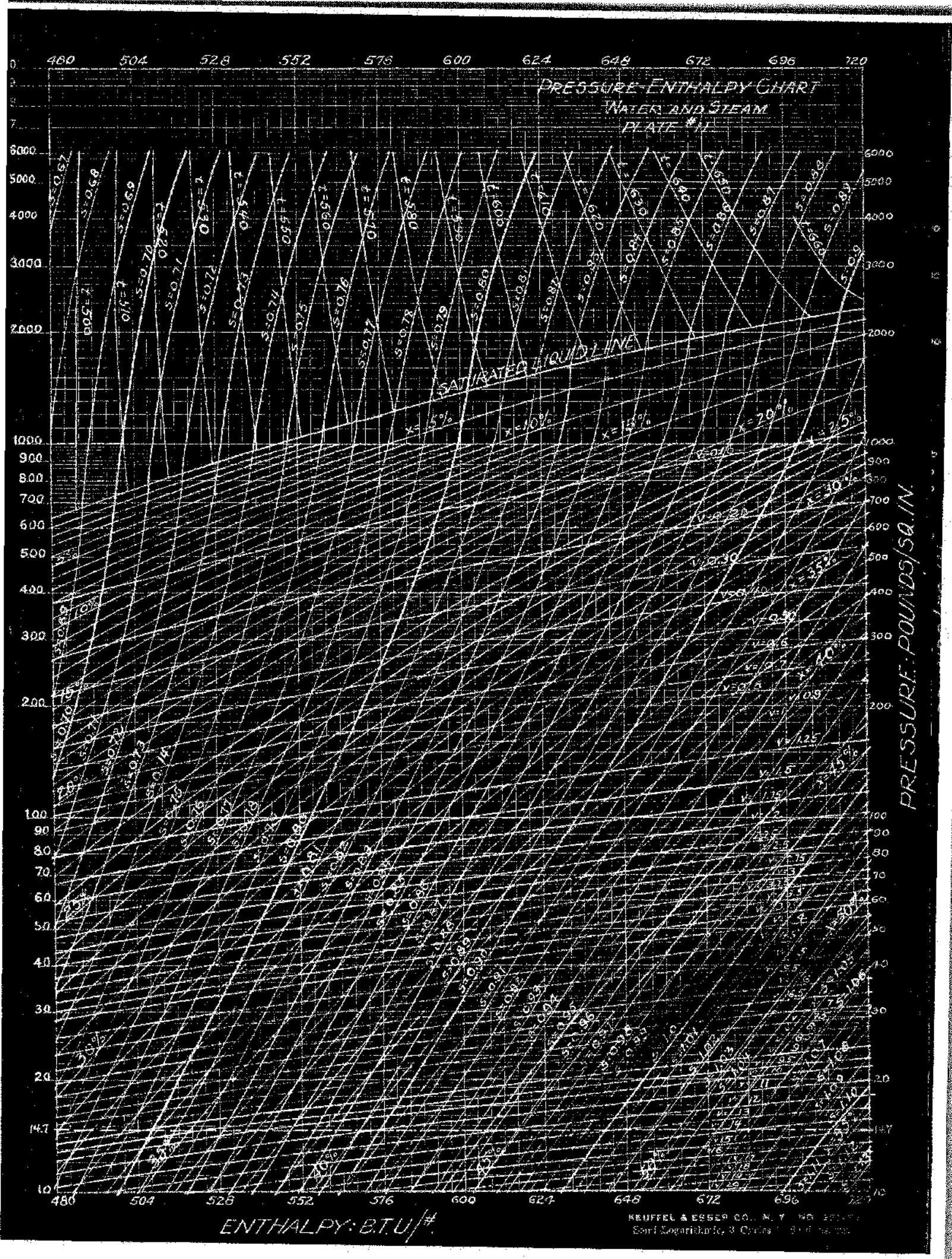

960
984
1008
1032
1056
1080
1104
1128
1152
1176
1200
PRESSURE: POUNDS/SQ IN.
ENTHALPY: B.T.U./#.
SATURATED STEAM LINE
PRESSURE-ENTHALPY CHART.
WATER AND STEAM.
PLATE #6
KRUFFEL & ESSER CO. N. Y.

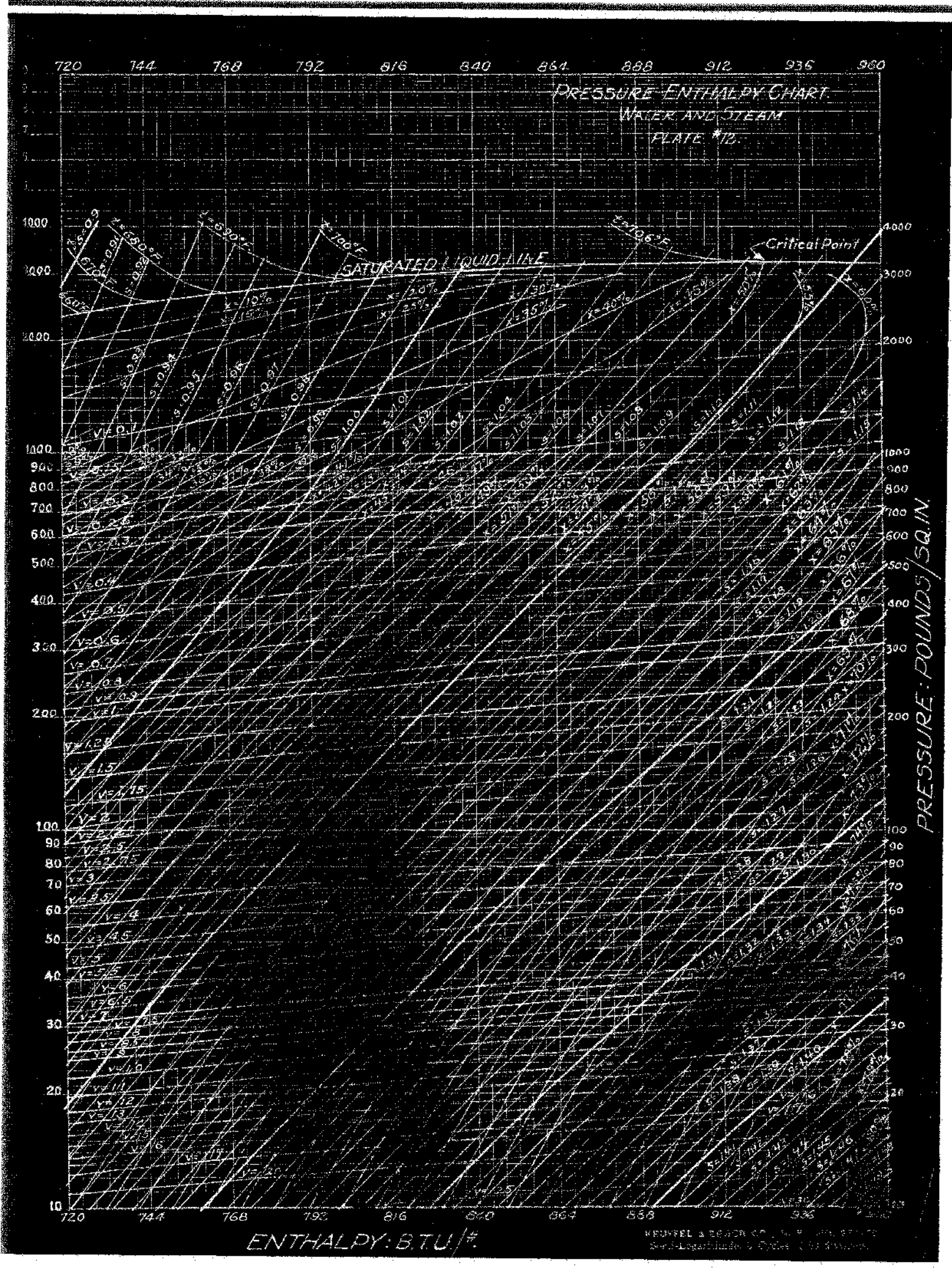

PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE # 1.
ENTHALPY: B.T.U./#
PRESSURE: POUNDS/SQ. IN.
KEUFFEL & ESSER CO., N. Y.
Semi-Logarithmic, 3 Cycles x 50 Divisions

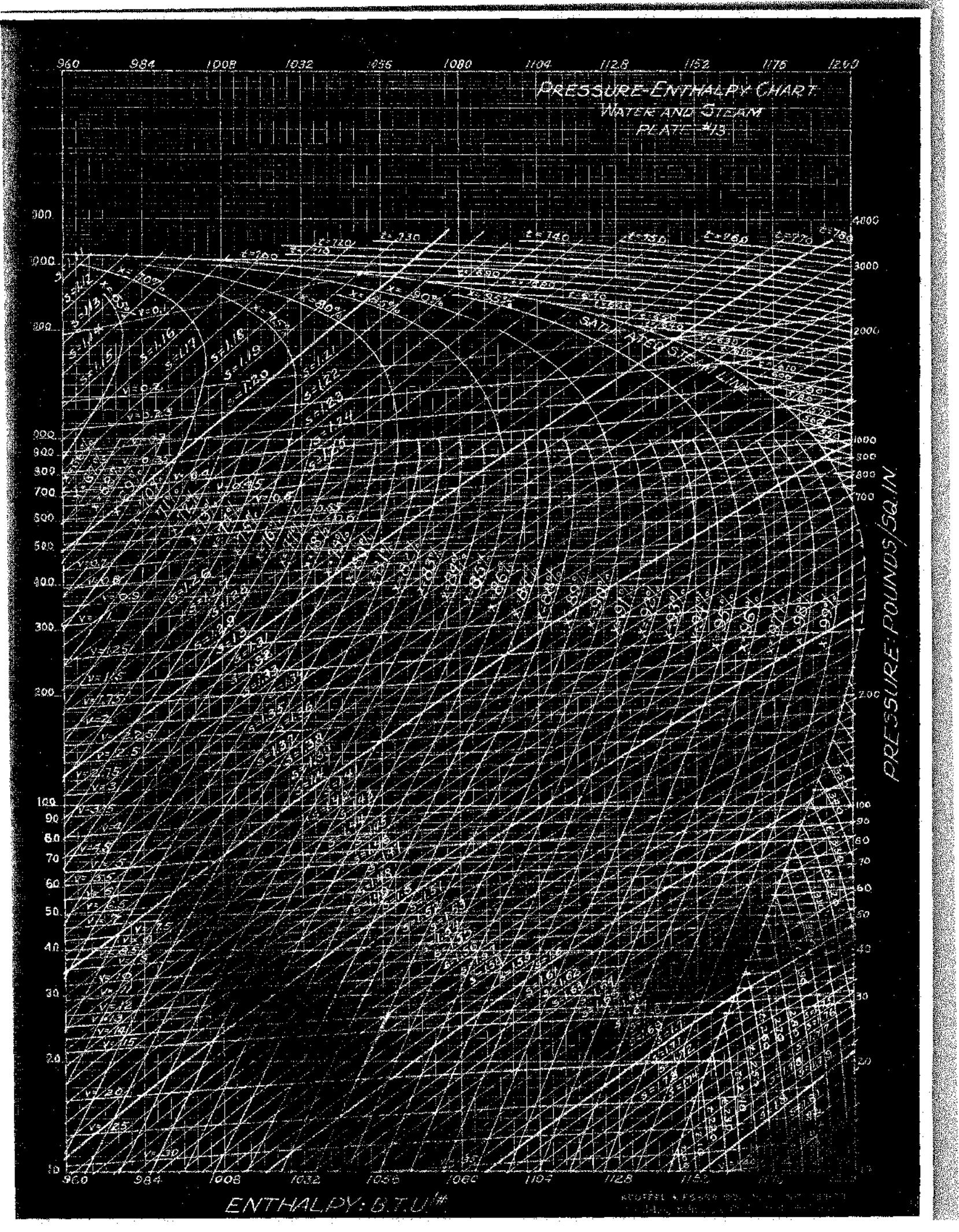

1440
1464
1488
1512
1536
1560
PRESSURE: POUNDS/SQ. IN.
ENTHALPY: B.T.U./#.
PRESSURE-ENTHALPY CHART.
WATER AND STEAM
PLATE #8.
KEUFFEL & ESSER CO., N. Y.

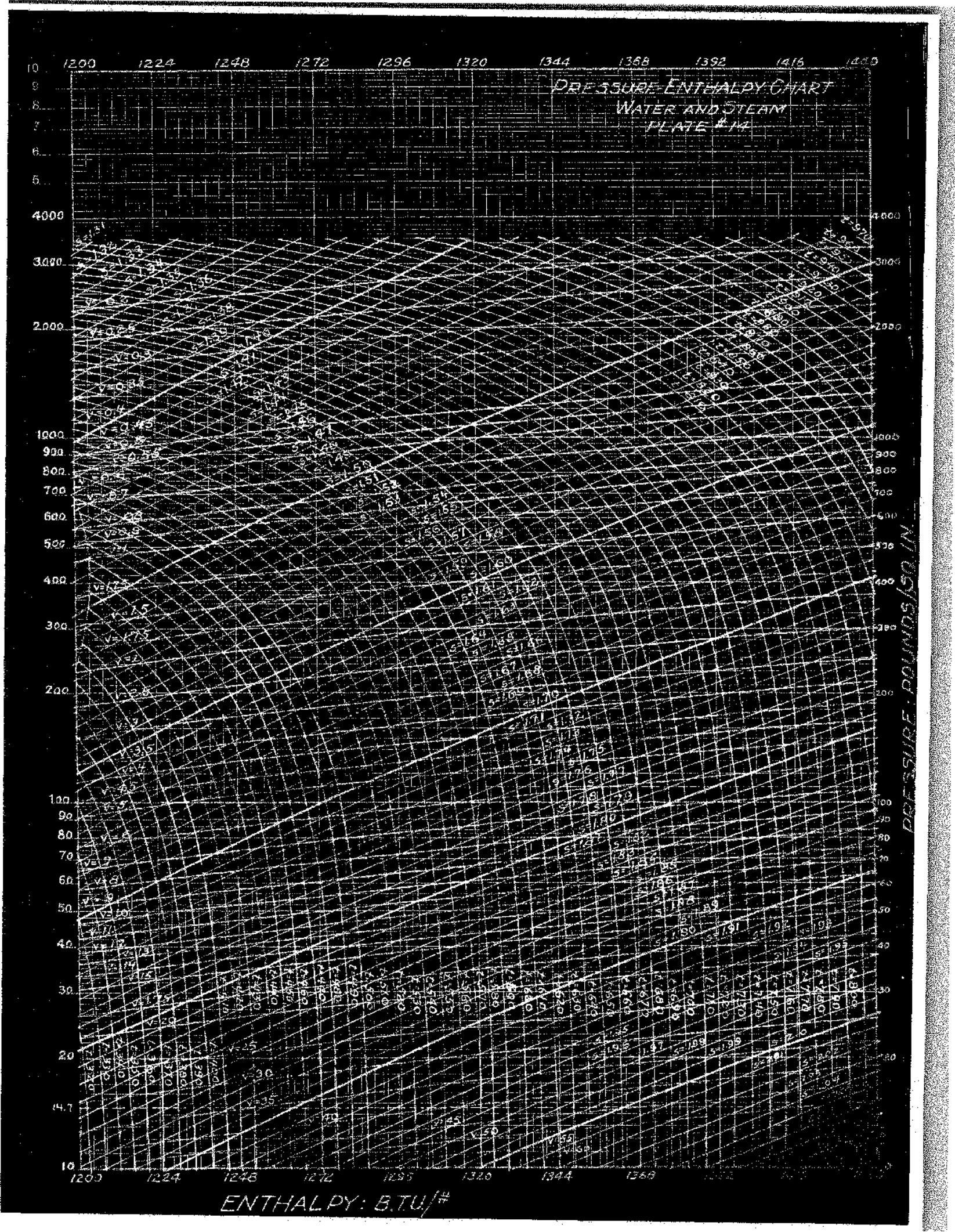

PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #3
ENTHALPY: B.T.U./#
PRESSURE: POUNDS/SQ. IN.
KEUFFEL & ESSER CO.

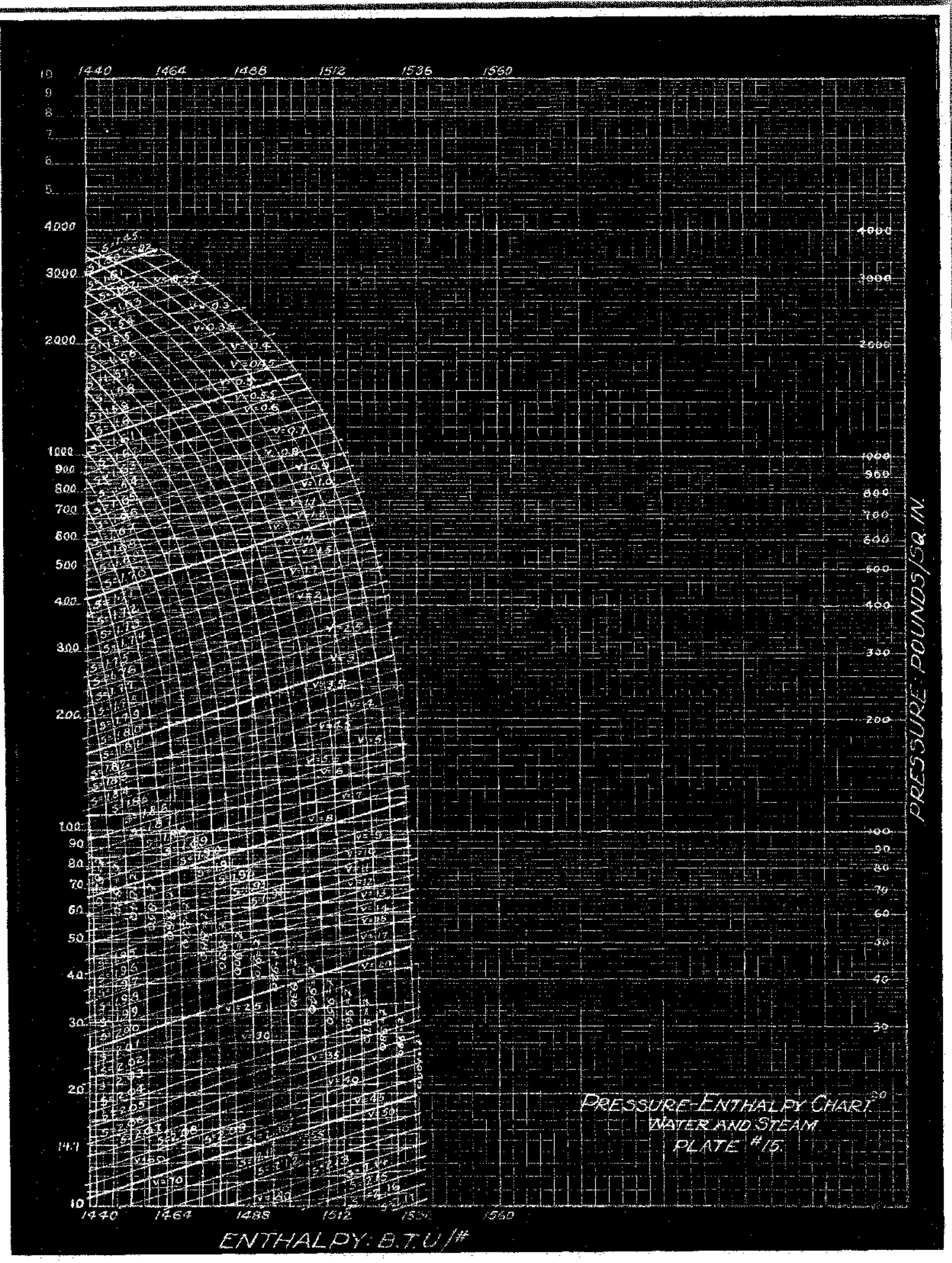

PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #10
240 264 288 312 336 360 384 408 432 456 480
6000 5000 4000 3000 2000 1000 900 800 700 600 500 400 300 200 100 90 80 70 60 50 40 30 20 10
SATURATED LIQUID LINE
PRESSURE: POUNDS/SQ. IN.
ENTHALPY: B.T.U./#.
KEUFFEL & ESSER CO.


PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #12
SATURATED LIQUID LINE
ENTHALPY: B.T.U/#
PRESSURE: POUNDS/SQ.IN.
480
504
528
552
576
600
624
648
672
696
720
6000
5000
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
14.7
10
REUFFEL & ESSER CO., N. Y.


PRESSURE ENTHALPY CHART
WATER AND STEAM
PLATE #12
SATURATED LIQUID LINE
Critical Point
ENTHALPY: B.T.U./#
PRESSURE: POUNDS/SQ.IN.
720
744
768
792
816
840
864
888
912
936
960
1000
2000
3000
4000
100
200
300
400
500
600
700
800
900
1000
10
20
30
40
50
60
70
80
90
100


PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #13
960
984
1008
1032
1056
1080
1104
1128
1152
1176
1200
ENTHALPY: B.T.U.#
PRESSURE: POUNDS/SQ.IN.
SATURATED STEAM LINE
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
10


PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE # 14
1200
1224
1248
1272
1296
1320
1344
1368
1392
1416
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
14.7
10
PRESSURE: POUNDS/SQ IN
ENTHALPY: B.T.U/#


1440
1464
1488
1512
1536
1560
4000
3000
2000
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
40
30
20
14.7
10
PRESSURE: POUNDS/SQ IN.
ENTHALPY: B.T.U/#
PRESSURE-ENTHALPY CHART
WATER AND STEAM
PLATE #15.

PRESSURE TEMPERATURE RELATIONS.

NOTE: These relations between saturated temperatures and pressures are taken from those listed in "Steam Tables and Diagrams" by Keenan. The Column headed "P" is pounds per square inch except where designated as " Hg. The column headed by "T" is degrees Fahrenheit.

P.	T.	P.	T.	P.	T.	P.	T.
0.20	53.15	2.8	138.80	29.0	248.40	64.0	296.94
		3.0	141.49	30.0	250.34	65.0	297.97
0.5" Hg.	58.83	3.5	147.59	31.0	252.22	66.0	298.98
		4.0	152.99	32.0	254.05	67.0	299.99
0.25	59.32	4.5	157.83	33.0	255.84	68.0	300.98
0.30	64.49						
0.35	68.95	5.0	162.25	34.0	257.58	69.0	301.96
		5.5	166.31	35.0	259.28	70.0	302.92
0.75"Hg.	70.44	6.0	170.07	36.0	260.94	71.0	303.88
		6.5	173.55	37.0	262.57	72.0	304.82
0.40	72.88	7.0	176.85	38.0	264.16	73.0	305.76
0.45	76.40						
		7.5	179.94	39.0	265.72	74.0	306.68
1.0" Hg.	79.06	8.0	182.87	40.0	267.24	75.0	307.60
		8.5	185.64	41.0	268.74	76.0	308.50
0.50	79.60	9.0	188.28	42.0	270.21	77.0	309.39
0.60	85.21	9.5	190.82	43.0	271.65	78.0	310.28
0.70	90.09						
		10.0	193.21	44.0	273.06	79.0	311.16
1.5" Hg.	91.75	11.0	197.75	45.0	274.45	80.0	312.03
		12.0	201.96	46.0	275.81	81.0	312.88
0.80	94.40	13.0	205.88	47.0	277.14	82.0	313.74
0.90	98.26	14.0	209.56	48.0	278.45	83.0	314.58
2.0" Hg.	101.17	14.7	212.00	49.0	279.74	84.0	315.42
		15.0	213.03	50.0	281.01	85.0	316.25
1.0	101.76	16.0	216.32	51.0	282.26	86.0	317.06
1.2	107.94	17.0	219.43	52.0	283.49	87.0	317.88
		18.0	222.40	53.0	284.70	88.0	318.68
2.5" Hg.	108.73						
		19.0	225.23	54.0	285.90	89.0	319.48
1.4	113.28	20.0	227.96	55.0	287.07	90.0	320.27
		21.0	230.56	56.0	288.23	91.0	321.05
3.0" Hg.	115.08	22.0	233.07	57.0	289.37	92.0	321.83
		23.0	235.49	58.0	290.50	93.0	322.60
1.6	118.00						
1.8	122.25	24.0	237.82	59.0	291.62	94.0	323.37
		25.0	240.07	60.0	292.71	95.0	324.13
2.0	126.10	26.0	242.25	61.0	293.79	96.0	324.88
2.2	129.63	27.0	244.36	62.0	294.85	97.0	325.62
2.4	132.91	28.0	246.41	63.0	295.91	98.0	326.37
2.6	135.94						

P.	T.	P.	T.	P.	T.	P.	T.
99.0	327.10	134.0	349.64	169.0	367.94	220.0	389.89
100.0	327.83	135.0	350.21	170.0	368.42	225.0	391.81
101.0	328.55	136.0	350.78	171.0	368.90	230.0	393.70
102.0	329.27	137.0	351.35	172.0	369.37	235.0	395.56
103.0	329.98	138.0	351.91	173.0	369.84	240.0	397.40
104.0	330.68	139.0	352.47	174.0	370.31	245.0	399.20
105.0	331.38	140.0	353.03	175.0	370.78	250.0	400.97
106.0	332.08	141.0	353.59	176.0	371.24	255.0	402.71
107.0	332.76	142.0	354.14	177.0	371.70	260.0	404.43
108.0	333.44	143.0	354.68	178.0	372.16	265.0	406.12
109.0	334.12	144.0	355.22	179.0	372.62	270.0	407.79
110.0	334.79	145.0	355.77	180.0	373.08	275.0	409.44
111.0	335.46	146.0	356.31	181.0	373.54	280.0	411.06
112.0	336.12	147.0	356.84	182.0	374.00	285.0	412.66
113.0	336.78	148.0	357.37	183.0	374.45	290.0	412.24
114.0	337.43	149.0	357.90	184.0	374.90	295.0	415.80
115.0	338.08	150.0	358.43	185.0	375.34	300.0	417.33
116.0	338.72	151.0	358.95	186.0	375.78	310.0	420.35
117.0	339.37	152.0	359.47	187.0	376.23	320.0	423.29
118.0	340.01	153.0	359.99	188.0	376.67	330.0	426.16
119.0	340.64	154.0	360.51	189.0	377.11	340.0	428.96
120.0	341.26	155.0	361.02	190.0	377.55	350.0	431.71
121.0	341.88	156.0	361.53	191.0	377.99	360.0	434.39
122.0	342.50	157.0	362.04	192.0	378.42	370.0	437.01
123.0	343.12	158.0	362.54	193.0	378.85	380.0	439.59
124.0	343.73	159.0	363.05	194.0	379.27	390.0	442.11
125.0	344.34	160.0	363.55	195.0	379.70	400.0	444.58
126.0	344.94	161.0	364.05	196.0	380.13	410.0	447.00
127.0	345.54	162.0	364.54	197.0	380.55	420.0	449.38
128.0	346.14	163.0	365.03	198.0	380.97	430.0	451.72
129.0	346.73	164.0	365.52	199.0	381.40	440.0	454.01
130.0	347.31	165.0	366.01	200.0	381.82	450.0	456.27
131.0	347.90	166.0	366.50	205.0	383.89	460.0	458.48
132.0	348.48	167.0	366.98	210.0	385.93	470.0	460.66
133.0	349.06	168.0	367.46	215.0	387.93	480.0	462.80

P.	T.	P.	T.
490.0	464.91	1200.0	567.14
500.0	466.99	1250.0	572.30
520.0	471.05	1300.0	577.32
540.0	474.99	1350.0	582.21
560.0	478.82	1400.0	586.96
580.0	482.55	1450.0	591.58
600.0	486.17	1500.0	596.08
620.0	489.79	1600.0	604.74
640.0	493.16	1700.0	612.98
660.0	496.53	1800.0	620.86
680.0	499.82	1900.0	628.39
700.0	503.04	2000.0	635.6
720.0	506.19	2100.0	642.6
740.0	509.28	2200.0	649.2
760.0	512.30	2300.0	655.7
780.0	515.27	2400.0	661.9
800.0	518.18	2500.0	668.0
820.0	521.03	2600.0	673.8
840.0	523.83	2700.0	679.5
860.0	526.58	2800.0	684.9
880.0	529.29	2900.0	690.2
900.0	531.95	3000.0	695.2
920.0	534.56	3100.0	700.2
940.0	537.13	3200.0	704.9
960.0	539.66	3226.0	706.1
980.0	542.14		
1000.0	544.58		
1050.0	550.53		
1100.0	556.28		
1150.0	561.81		

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